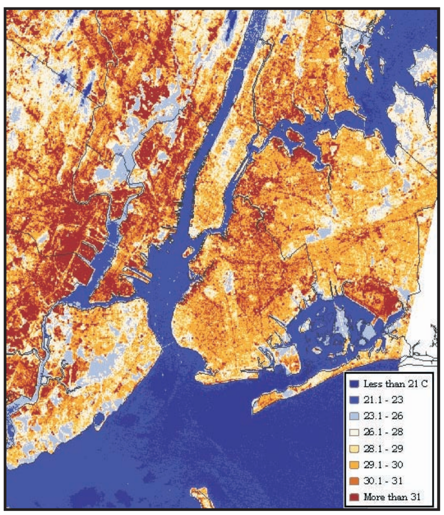
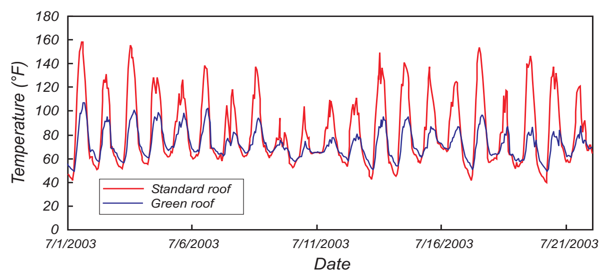
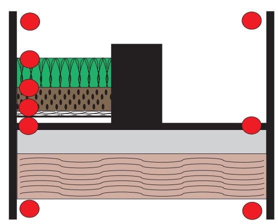
Green Roofs in the New York Metropolitan Region

Research Report







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Preface

Cynthia Rosenzweig

Science in Action

This report is the result of a confluence of trends that signal further integration of scientific knowledge and methods, and practical mechanisms for achieving urban sustainability. This integration was the founding principle for the current study.

Recent research has provided a much greater understanding of the complexities and interactions of the physical, biophysical, and social realms of the urban environment. Areas of particular focus are the urban heat island, the urban biosphere, urban hydrology, and climate change.

The challenge of integration across scales permeates urban research, as questions and hypotheses, methods and analyses shift from individual buildings, to neighborhoods, boroughs, cities proper, and metropolitan regions. Global climate and hydrological models need to be downscaled, while building-level energy analyses need to be upscaled to analyze questions related to individual and social functions of ecological infrastructure.

We also recognize that it is time for scientists and scholars to play an integrative role in public policy arenas pertaining to the urban environment, especially in regard to its sustainability and resilience to global change. As always, however, scientists need to maintain commitment to objectivity and the delineation of key uncertainties. This more immediate role is, in part, influenced by the growing scientific evidence of global warming. For researchers in post 9/11 New York, and Hurricane Katrina New Orleans, there is a sense, too, of a desire to contribute to creating a more fully functional urban environment as part of the recovery process.

Green Roofs in the New York Metropolitan Region
Research Report

Executive Summary

New York City faces a suite of extant and emergent environmental and human health challenges in the 21st century. The need to understand the nature of these challenges, and to evaluate potential mitigation and adaptation strategies, requires innovative scientific research and assessment, coupled with sound policy development, land-use planning, technological innovation, and urban development. This study explores the development of 'green' or vegetated rooftops in New York City—a technology that has been implemented in municipalities around the world as a strategy for mitigating such challenges as stormwater runoff pollution and high urban temperatures.

A green roof is a roofing assembly consisting of a waterproof membrane and additional component layers – including growing media, drainage, and root protection – allowing for the propagation of vegetation across all or part of a roof surface. Widespread adoption of green roofs as a roofing technology can potentially address multiple environmental and human health problems in New York City, including the urban heat island effect, global climate change, and stormwater runoff. However, locally collected data and validated models are needed to demonstrate how green roofs will function as part of the urban infrastructure. Our objective is to quantify the environmental functions and economic benefits and costs of green roof adoption in New York City.

In this report, we focus on green roofs that are lightweight, thin (4–6 inches of growing medium), and planted with hardy, drought-resistant plants to minimize weight, cost, and maintenance. This type of green roof is generally referred to as 'extensive'. However, green roofs can also be designed to support grass, flowers, trees, shrubs, and/or crops and thus serve as an additional building outdoor space and amenity. This type of green roof is generally referred to as 'intensive.'

Green roofs provide multiple environmental benefits by integrating the natural cooling, insulating, and water-retention properties of soil and vegetation into city buildings. There are many potential benefits of green roofs, but we focus here on several key impact sectors. These are (1) energy use and global climate change, (2) the urban heat island effect, and (3) stormwater runoff. A set of greening scenarios is used to determine the effect of greening a single building as well as greening ten percent or fifty percent of the Newtown Creek sewage-shed (an artificial drainage basin corresponding to an area served by a single wastewater treatment plant) and New York City.

Our study takes an integrative approach to green roofs research. The goal is to provide policy-makers with information needed to evaluate green roofs as an urban design solution for New York City. Green roofs have the potential to change how urban environments, and the role of nature within them, are perceived.

Data Analysis and Modeling

The research methods consisted of data analysis, simulation models, geographical information systems (GIS) and cost-benefit calculations. Data collected at the Pennsylvania State University Center for Green Roof Research directly demonstrate significant reductions in rooftop temperatures that may be achieved with vegetation. To study the impact of green roofs on the urban heat island effect, satellite

imagery, GIS software, and local meteorological data are used. Penn State data on rainfall and runoff are also analyzed and compared to results obtained using a simple box model and local meteorological data for New York City. We are designing a green roof research station in New York City to monitor green roof performances, develop improved simulation models, and work with local schools. A cost-benefit analysis is done that includes both private and public aspects of green roofs.

Key Findings

Energy

- By cooling the surface of a roof, green roofs can help the region prepare to adapt to global warming, and potentially reduce energy usage, fossil fuel consumption, and greenhouse gas emissions, the cause of global warming.
- Surface temperatures (at the roof membrane) on standard roofs can be more than 72°F (40°C) higher than on green roofs at midday in the summer.
- On average, surface temperatures in July 2003 were 34°F (19°C) higher on the standard roofs during the day and 14°F (8°C) lower at night (Figure E-1).
- Indoor air temperatures were on average 4°F (2°C) lower in the buildings with green roofs during the day and 0.5°F (0.3°C) higher at night.
- Simulations with our rooftop energy balance model calibrated and validated with observational data from Penn State show how bright white roofs would need to be to reduce roof surface temperature and heat flux into buildings as much as green roofs do.
- Follow-on work includes simulating percentage reduction in heat flow and energy demand for cooling for various green roof systems and building types.

Urban Heat Island

- By providing a vegetated surface, green roofs may reduce outdoor air temperature and the urban heat island effect through evapotranspiration, shading, and increased albedo.
- Satellite data show that surface heating varies by neighborhood, with 'hotspots' at airports and in parts of the Bronx, Brooklyn and Queens

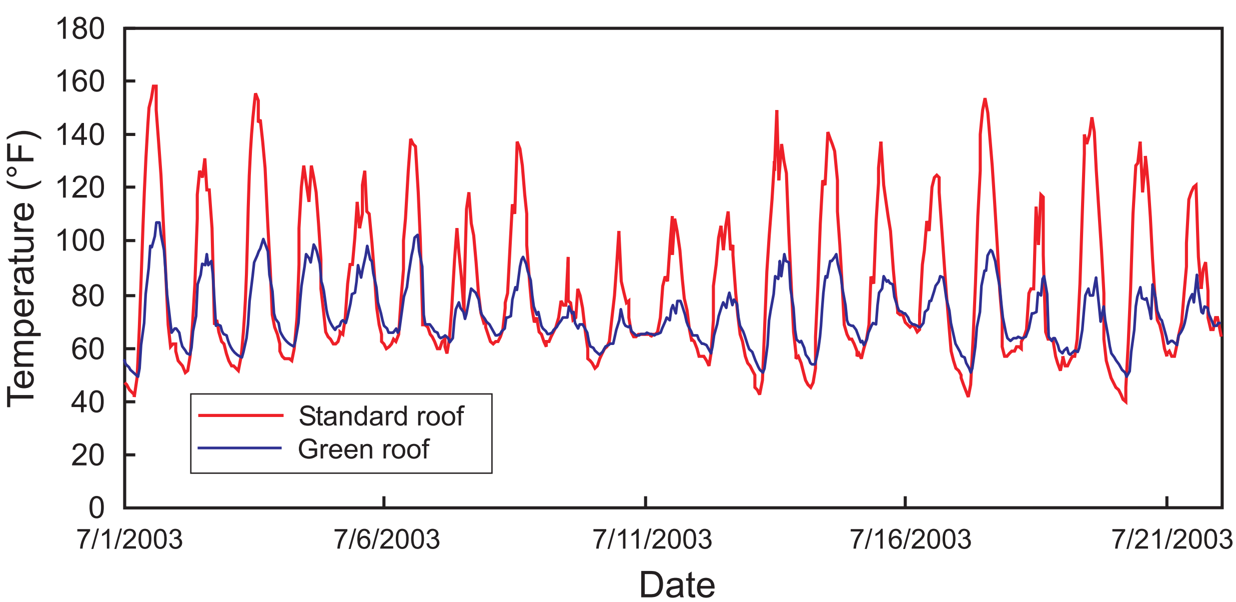

Figure E-1. Average surface temperature on green roofs and standard roofs at Penn State Center for Green Roofs Research. (Data provided by Dr. David Beattie.)

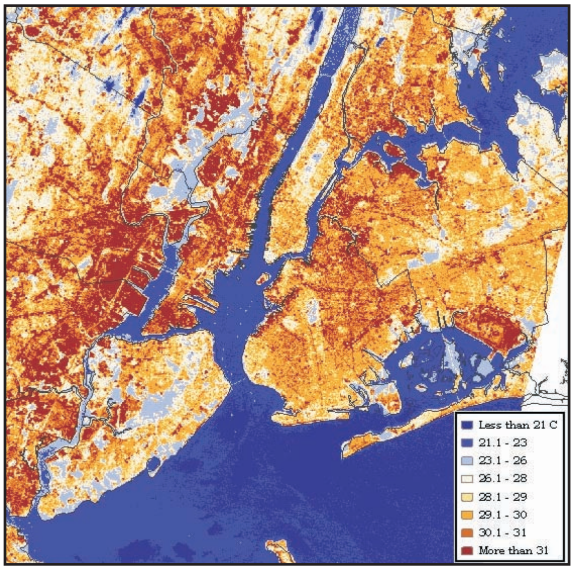

Figure E-2. Thermal map of surface temperature in the New York metropolitan region. Landsat ETM 7, August 14 2002, 10:30 AM, Band 6.

(Figure E-2).

- A 50% extensive green roof scenario reduced New York City's average surface temperature by 0.1 – 1.4°F (<0.1 – 0.8°C).
- Green roofs may provide a beneficial environmental modification that protects against two current public health stressors: high summertime heat and ground-level ozone.
- Follow-on work includes simulating the impact of green roofs on summertime air temperature using the MM5 mesoscale climate model.

Hydrology

- By retaining, evaporating, and delaying runoff, green roofs can reduce combined stormwater-sewage overflows (CSOs). Approximately 80% of New York City operates on a combined sewer system and currently only about 61% of rainwater is treated annually. CSOs discharge untreated sewage and stormwater into water bodies surrounding New York City.
- Analysis of Penn State data show that green roofs captured 80% of rainfall during rainstorms, compared to 24% for standard roofs (Table E-1).
- Simulation of green-roof rainfall retention using a simple box model and data from LaGuardia airport for 1984 (a wet year) and 1988 (a normal year) show that runoff could be reduced by up to 10% at the sewage-shed scale with a 50% green roof infrastructure scenario.
- Follow-on work includes simulation of CSO volume reduction at the sewage-shed and city-wide scales using the EPA Stormwater Management Model (SWMM), New York City rainfall data, and data on green roof performance.

Table E-1. Rainfall retention on standard roofs and green roofs at Penn State Center for Green Roofs Research, June–September, 2003.

Rainfall retained (%)	**Standard roof**	**Green roof**
Average retention	24%	80%
Retention at peak runoff	26%	74%

Green Roof Research Station

A central goal for our work is the development of a rooftop research station to collect data about green roof performance in New York City (Figure E-3). The experimental design for the research station requires a minimum of 3 green plots and 1 control plot, all with equal area. This design allows for comparison between a green roof and a standard roof as well as between two different substrate depths and two different plant mixes. It also allows for models to be run with different green roof configurations to determine the sensitivity to changes in key variables — for example, soil depth or plant type. Using the research station as a laboratory, monitoring protocols that can be easily and inexpensively replicated at other green roof sites in New York can be designed and tested. As initial research questions regarding energy and hydrology become resolved, the Green Roof Research Station will continue to provide a laboratory for researching new urban sustainability questions in the coming years.

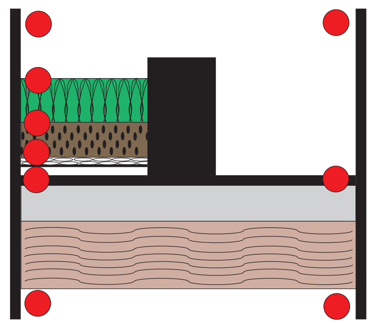

Figure E-3. Green Roof Research Station temperature monitoring points.

Costs and Benefits

Environmental cost-benefit analysis is a decision-support tool that provides a format for enumerating the range of benefits and costs surrounding a decision, aggregating the effects over time by discounting future dollars into present terms, and arriving at a dollar-denominated present value that can be compared with other uses for scarce financial resources. The cost-benefit analysis is divided into two tiers. Tier I includes the benefits and costs of green roofs related to an initial set of factors. Tier II includes possible additional benefits such as improved air quality from pollutant filtering and increased property values. Included benefits and costs are listed in Table E-2. Preliminary results of the cost-benefit analysis for a 50% green roof infrastructure scenario in New York City are shown in Table E-3. The analysis indicates that green roofs may not be cost-effective at the individual building level for a limited set of factors, green roof infrastructure is cost-effective when the full range of benefits is considered at private and public scales.

Table E-2. Private and public benefits and costs of green roofs.

Private (building-level) benefits	Public (city-level) benefits
Increased service life for roof membrane	Reduced stormwater runoff expenditures
Reduced energy use for cooling	Reduced urban heat island
Sound insulation	Improved air quality
Food production	Reduced greenhouse gas emissions
Aesthetic value	Improved public health
	Aesthetic value
Private costs	**Public costs**
Net cost of green roof	Program administration and setup*
Maintenance costs	

*A green roof infrastructure program would likely require administrative support at the municipal level.

Table E-3. Preliminary cost-benefit analysis results for Tier I (research areas covered in this report related to energy, hydrology, and the urban heat island) and Tier II (additional potential benefits and costs of green roofs in New York City).

Tier I & Tier II results	Performance scenario*		
Tier I	**Low**	**Medium**	**High**
Benefit-Cost Ratio Tier I, Private	0.34	0.46	1.31
Benefit-Cost Ratio Tier I, Public	0.53	0.65	1.57
Tier II	**Low**	**Medium**	**High**
Benefit-Cost Ratio Tier I & II, Private	0.38	0.54	1.85
Benefit-Cost Ratio Tier I & II, Public	0.66	1.02	3.87

*The medium performance scenario is based on the best guess for each parameter. The low and high scenarios are used to illustrate the range of benefits and costs associated with extensive green roofs.

Conclusions

Green roof infrastructure could be a cost-effective way to help solve some of New York City's environmental and human health problems, when multiple private and public benefits are considered together. In North America, green roofs are still a relatively new ecological infrastructure. Therefore, New York City has an opportunity to be a trend-setter in the green roof arena.

Recommendations

Recommendations for first steps that could be taken toward policy development in New York City are:

- Develop green roof demonstration projects for testing and monitoring at both the building and neighborhood scales;
- Design and implement appropriate government programs to support establishment of green roofs at the neighborhood scale; and
- Include ecological infrastructure in New York City and New York State environmental decision-making.

Introduction and Study Methods

Cynthia Rosenzweig, Stuart Gaffin, and Lily Parshall

New York City faces a suite of extant and emergent environmental and human health challenges in the twenty-first century. The need to understand the nature of these challenges, and to evaluate potential adaptation and mitigation strategies, requires scientific research and assessment, coupled with sound policy analysis, technological innovation, and urban development. Our overall goal is to conduct multidisciplinary research that investigates the form and function of ecological infrastructure for New York City's built environment and landscape. The study explores the development of 'green' or vegetated rooftops in New York City as a strategy for mitigating such challenges as stormwater-runoff pollution and high urban temperatures.

A green roof is a roofing assembly consisting of a waterproof membrane and additional component layers – including growing media, drainage, and root protection – allowing for the propagation of vegetation across all or part of a roof surface. Widespread adoption of green roofs as a roofing technology can potentially address multiple environmental and human health problems in New York City, including the urban heat island effect, global climate change, and stormwater runoff. However, locally-collected data and validated models are needed to demonstrate how green roofs will function as part of the urban infrastructure.

This report is the result of a partnership between researchers from the Columbia Earth Institute, Hunter College of CUNY, and other research organizations in the New York metropolitan region. Our objective is to quantify the environmental functions and economic benefits and costs of green roof adoption in New York City. In this report we describe our methodology and present results from three key impact sectors: energy, urban heat island, and hydrology. We describe our development of a Green Roof Research Station for experiments and data collection. We then present an integrated cost-benefit analysis of potential green roof functions in New York City. Finally, we consider the potential of green roofs to change how urban environments, and the role of nature within them, are perceived.

This work is integrative in its approach to green roofs research. Our goal is to provide policy-makers with the information needed to develop green roofs as a pragmatic, restorative, and visionary urban design solution for some of New York City's urban environmental problems.

Green Roofs

A green roof system typically consists of several layers including a waterproof membrane, drainage layer, growing medium, and vegetation (Figure 1). These layers may be part of a pre-fabricated roofing assembly system, or each layer may be installed separately. A green roof system is designed based on the goals and constraints of a particular project. Green roofs can be lightweight, thin, and planted with hardy, drought-resistant plants to minimize weight, cost, and maintenance. This type of green roof is generally referred to as 'extensive.' However, green roofs can also be designed to support grasses, flowers, trees, shrubs, or crops. This type of green roof is generally referred to as 'intensive.' Examples of different types of green roofs are shown in Figure 2.

Some regions — for example, the British Isles and the Swiss Alps — have a centuries-long tradition of vegetated rooftops, precursors to modern green roof systems, which usually took the form of peat-roofed houses. Modern green roofs have been used to improve urban environments in Europe since the early 1970s, with Germany emerging as a key leader. In 2001 alone, fourteen percent of flat roofs

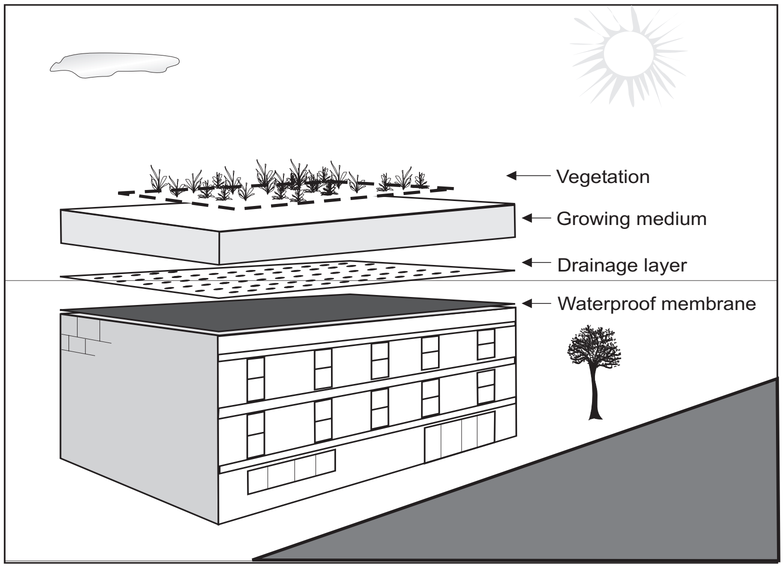

Figure 1. Diagram of a green roof system.

constructed on new buildings in Germany were green roofs, accounting for approximately 145 million square feet (13.5 million square meters) (Jahrbuch Dachbegruenung, 2002). In North America, municipally supported green roof programs and green roof demonstration projects are underway in Portland, Chicago, and Toronto, among other cities.

Environmental Benefits of Green Roofs

Green roofs provide multiple environmental benefits by integrating the natural cooling, insulating, and water-retention properties of soil and vegetation into city buildings (Table 1). Green roofs also have the potential to change how urban environments, and the role of nature within them, are perceived, subsequently helping to inspire more sustainable behaviors and attitudes toward human-nature interactions. While a wide range of public and private benefits of green roofs are possible in New York City – including service life extension of roofing materials, property value increase, increased biodiversity, and agricultural potential – we focus here on energy use and global climate change, the urban heat island effect, and stormwater runoff.

Energy Use and Global Climate Change

By moderating temperature inside a building, green roofs can help the region prepare to adapt to global warming by reducing energy usage, fossil fuel consumption, and greenhouse gas emissions (the cause of global warming). By cooling the surface, the green roof reduces the flow of energy into and out of a building, thus reducing the need for space heating and cooling. One-sixth of all electrical energy used in the

Table 1. Private and public benefits and costs of green roofs.

Private (building-level) benefits	**Public (city-level) benefits**
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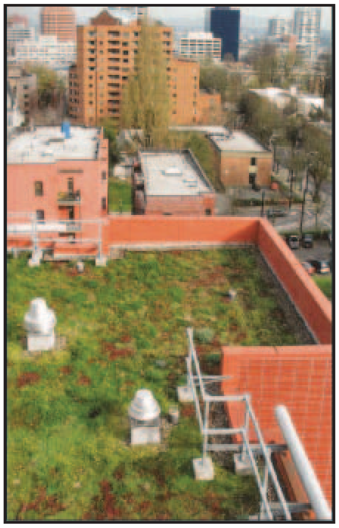
(a)



(b)

Figure 2. Green roofs with brief descriptions
a) Hamilton West Apartments, Portland OR. Source: Portland Ecoroof Tours Brochure, Environmental Services, City of Portland.
b) Chicago City Hall. Source: Dunnett and Kingsbury, *Planting GreenRoofs and Living Walls*, 2004.

United States is for space cooling (Rosenfeld et al., 1997). A green roof is particularly effective at reducing the need for air-conditioning in the summertime (Liu, 2003).

Two global climate models project that the New York metropolitan region will experience a warming of 1.6–3.4°F (0.9–1.9°C) in the 2020s, 2.5–6.5°F (1.4–3.6°C) in the 2050s, and 4.3–10.3°F (2.4–5.7°C) in the 2080s due to anthropogenic greenhouse gas emissions (Rosenzweig and Solecki, 2001). Such an increase in temperature would lead to stress upon the electric system during heat waves and may lead to daily peak load increases from 7 to 12% in the 2020s to 11 to 16% in the 2080s (Hill and Goldberg, 2003).

Urban Heat Island Effect

By providing a vegetated surface, green roofs may reduce the outdoor air temperature and the urban heat island effect through evapotranspiration and shading, depending upon the original roof surface and the vegetation chosen. The urban heat island (UHI) effect is the documented increase in urban temperature compared to surrounding suburban and rural temperature. A heat island develops when built surfaces (concrete, asphalt, brick) that have high heat capacities and are impervious to water replace natural surfaces that moderate temperature through evapotranspiration and shading (Akbari et al., 1992). Estimates of the urban heat island effect for New York City range between 3.6 and 7.2°F (2–4°C) (Rosenzweig and Solecki, 2001; Gedzelman et al., 2004). The impacts of the UHI include increases in energy demand, heat stress and air pollution-related illnesses, and emissions of carbon dioxide and other pollutants due to higher energy demand.

Stormwater Runoff

By retaining, evaporating, and detaining runoff, green roofs can reduce combined stormwater-sewage overflows. New York City has a combined sewage overflow (CSO) system, meaning that stormwater runoff and sewage share the same treatment system. As New York City's population has grown over the past century, the amount of sanitary sewage from buildings has increased, and the amount of impervious surfaces — roads and building rooftops — has also grown. Currently, New York City's fourteen wastewater treatment facilities are unable to treat all sanitary sewage and stormwater during certain rainfall events. During instances when flow exceeds the system capacity, a certain portion of the combined sewage is discharged into city waterways. Currently, only ~60% of rainfall is collected and treated annually (NYCDEP, 2001). The New York City Department of Environmental Protection (NYCDEP) is mandated to control stormwater pollution and operates a $1.8 billion Citywide CSO Program to investigate options for further reducing pollution from stormwater runoff. (NYCDEP Division of Water Quality Improvement, 2002). A 1999 report to NYCDEP stated that vegetated roofs could have "significant feasibility" as an alternative to tank storage technologies in certain wastewater drainage basins (Copp et al., 1999).

Studying Green Roof Performance

Studies in the United States and abroad sponsored by local and regional governments, universities, and non-governmental organizations have quantified some of the environmental benefits of green roofs. Some studies have relied on *in situ* data collection by installing equipment to monitor the performance of green roofs, often calculating the difference between the green and control roofs. Other studies have developed energy balance, meteorological, and hydrological models to compare the theoretical performance of green roofs wtih standard roofs.

This report presents the studies conducted by a team of researchers based in the New York metropolitan region. This team has developed a methodological framework to support complementary data collection and modeling at various scales, from a single building to neighborhoods to New York City.

We are developing a Green Roof Research Station (the design and specification of which is presented in this report) to collect data in New York City. We also use data collected at an experimental green roof site at the Pennsylvania State University Green Roofs Research Center (Penn State) to calibrate and validate a rooftop energy balance model. Using the model, we are able to compare green roofs to standard roofs and to calculate reductions in heating and cooling requirements for buildings with green roofs. We also analyze Penn State data on rainfall and runoff and compare the results to those obtained using a simple box model and local meteorological data for New York. To study the impact of green roofs on the urban heat island effect, we use satellite imagery, GIS software, and local meteorological data.

Study Areas, Scenarios, and Scales

We have chosen two case studies for this report: the Newtown Creek sewage-shed (an artificial drainage basin corresponding to an area served by a single treatment plant) and New York City (Figure 3). The sewage-shed scale was chosen for its relevance to the hydrology sector and because it is a large enough area over which to study the urban heat island effect. Energy sector benefits begin at the building level, with reduced energy costs. Our energy balance model is set at a meter scale, but, to athe first-order, can be linearly scaled up to reflect available flat roof area within a sewage-shed or throughout the city.

Using these case study areas, each sector estimates the impacts of 10% and 50% rooftop greening scenarios. The case study areas and the flat roof areas associated with each scenario are listed in Table 2. Finally, we integrate sector results in the cost-benefit analysis to determine the overall environmental and economic impacts of green roofs.

Caveats and Uncertainties

In this report, we present research results based on our data analysis and modeling work to date. However, a limitation of this report is its use of data collected outside New York City (at Penn State) in an experimental, rather than a real-world setting.

Further, only one option for green roof plants is tested. The Penn State research roofs are extensive and are planted with sedum*s*, which are drought-resistant, low maintenance, hardy, and able to survive in thin and lightweight growing medium (Figure 4). Because sedum-based green roofs can be easily and relatively cheaply installed, we have chosen to focus our initial research on extensive roofs planted with sedum*s*. The choice of an extensive or intensive green roof and the selection of a planting palette depends on the primary purpose of the roof, the type of building, building usage, and microclimatic conditions.

Finally, our models simplify rooftop energy balance and rainfall-runoff relationships in order to obtain an initial estimate of potential green roof benefits; these models are being refined as the project progresses.

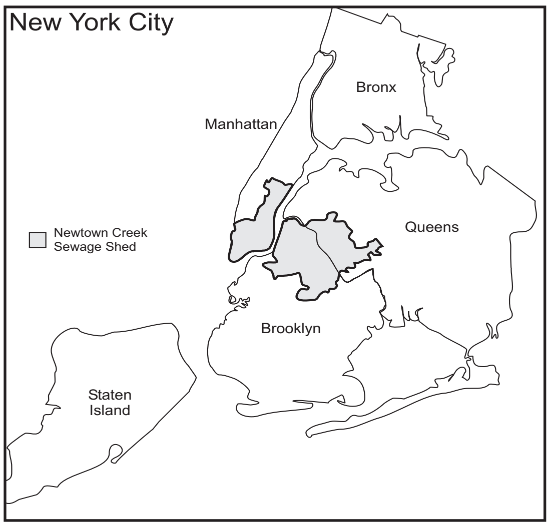


Figure 3. Case study boundaries.


Figure 4. *Sedum spurium* on one of the Penn State Green Roof Research Center roofs.

Table 2. Total flat roof areas associated with case studies and scenarios.

	Area		
Case study	**(square feet)**	**(square meters)**	
Newtown Creek	553,342,680	51,407,263	
New York City	8,238,546,360	765,386,679	
Scenarios	**10% (square feet)**	**10% (square meters)**	**approx. # roofs**
Newtown Creek	8,005,098	743,699	1,764
New York City	69,420,483	6,449,380	28,966
	50% (square feet)	**50% (square meters)**	**approx. # roofs**
Newtown Creek	40,025,488	3,718,493	15,281
New York City	347,102,415	32,246,898	144,832

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Energy Balance Modeling Applied to A Comparison of White and Green Roof Cooling Efficiency

Stuart Gaffin, Lily Parshall, Greg O'Keeffe, Dan Braman, David Beattie, and Robert Berghage

Introduction

In urban areas, rooftops comprise a substantial fraction of the total land surface area, which means their physical properties are important determinants of the urban environment. Typically black and impervious, traditional rooftops contribute directly to two ubiquitous urban environmental problems: the heat island effect and combined sewage-stormwater overflows (CSOs). For the building owner, dark roofs mean higher summertime energy consumption rates for cooling. Green rooftops, which have moderately higher albedos and which retain water that is evapotranspired to the atmosphere, can mitigate these problems, especially if they are implemented on a wide scale.

A simple methodology called 'energy balance' modeling is available to study the role of roofs in the urban heat island and building energy consumption rates (Oke, 1987). Energy balance refers to the physical fact that energy cannot be created nor destroyed so that the solar and longwave radiative energy received by a rooftop layer during any time interval must exactly equal, or 'balance,' the energy gained by that layer minus that lost from the layer during the same time interval. The physical equations that describe these gains and losses are widely used in climate studies (Oke, 1987).

Energy Flux Terms for Rooftops

There are seven energy flux[1] terms that are included in the energy balance. These are: (i) shortwave radiation downwards; (ii) shortwave radiation reflected upwards; (iii) longwave radiation downwards; (iv) longwave radiation emitted upwards; (v) sensible heat loss or gain; (vi) latent heat loss; and (vii) heat conduction downwards or upwards from the room below the roof (Figure 1). Equations for most of these flux terms are readily available from atmospheric science and heat transfer literature (Oke, 1987). The exceptions to this are the sensible heat flux, for which an 'all purpose' formula applicable to any building surface does not exist, and, to a lesser extent, the latent heat flux for complex vegetated surfaces.

Sensible heat transfer is a complex turbulence process involving winds, temperature gradients and boundary layer flows (Arnfield, 2003). As such, it is not possible to generalize for the many different building geometries and environments that exist. However urban climatology literature suggests that the surface-to-air temperature gradient and wind speed are dominant factors (Berdhal and Bretz, 1997; Terjung and Louie, 1974; Terjung and O'Rourke, 1980a,b; Wu, 2004). We adopt a formula with these two factors utilizing coefficients that we determine using roof monitoring data. The equations for our model, including the sensible heat flux, are given at the end of the chapter. For a theoretical discussion of energy relations on a green roof, see Appendix I.

Latent heat flow in our model is assumed to be zero for non-green roofs corresponding to the assumption that during non-rainfall periods, water is generally not present on the roof. This assumption is most valid during warm seasons when rainfall either drains or evaporates quickly from the rooftop. For green roofs, we adopt an approach used in some climate models for land surfaces: latent heat flux is assumed to be proportional to sensible heat flow with an inverse proportionality coefficient known as the 'Bowen ratio' (Oke, 1987; Hillel, 1998).

In this report we calibrate the model for the

[1] "Flux" means energy passing through a unit area per unit time, e.g. 'watts/meter^2' or 'BTU/foot^2 · hour'.

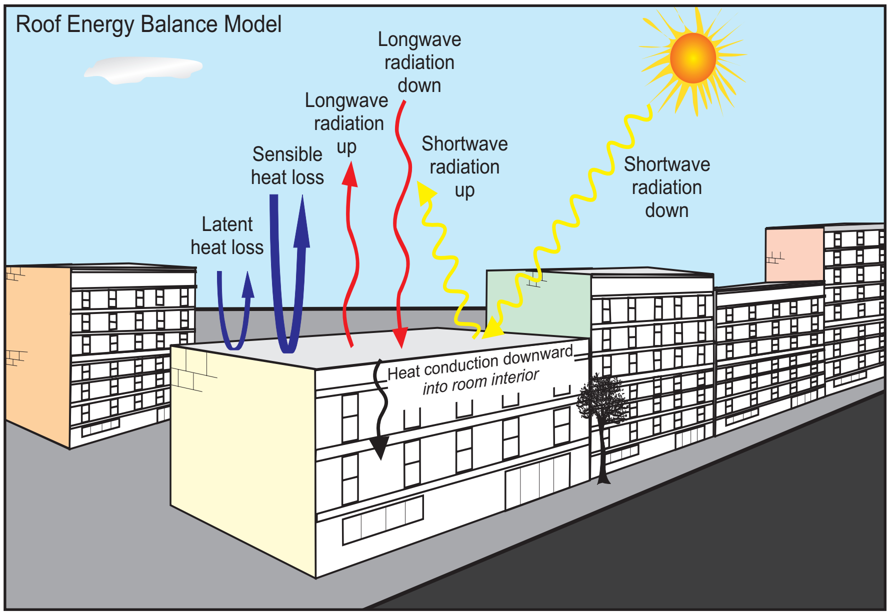

Figure 1. The seven energy fluxes considered in the energy balance model.

non-green roof and apply it to a comparison of the cooling power of white versus green surfaces. The statement of energy balance for the rooftop layer being monitored, expressed in terms of the seven energy fluxes and the heat capacity of the roof layer is:

$$SW_{down} - SW_{up} + LW_{down} - LW_{up} - Q_{convection} - Q_{conduction} - Q_{latent} = C_{roof} \frac{dT_{roof\text{-}layer\ average}}{dt} \qquad (1)$$

where SW, LW, $Q_{convection}$, $Q_{conduction}$ and Q_{latent} refer to shortwave, longwave, convection, conductive heat flow (into or from the room below) and latent heat transport, respectively.

The term on the right-hand-side of equation (1) is the rate of change of the heat content of the roof layer, which we calculate as the rate of change of the average roof-layer temperature times a heat-capacity coefficient for the roof-layer unit area. If the left-hand-side of equation (1) is positive, the roof layer is gaining more energy per unit time than it is losing. The gain in energy per unit time appears as, and is equal to, the rate of increase of the heat content of the roof layer.

Non-green rooftops, in most cases, are low mass systems to minimize structural load and, as such, cannot store much heat. They quickly reach a temperature that balances the heat and gain terms on the left-hand-side of the energy equation. Such systems are said to be in 'quasi-equilibrium' with the external forcing terms because the time delays are small between the actual temperature observed on the roof and the equilibrium temperature the roof would achieve if the forcing is held constant. In such cases, equation (1) can be simplified by setting the right-hand-side to zero. The resulting equation is a non-linear equilibrium system, rather than a non-linear delayed system (which is computationally easier to calculate).

Green roofs are often of low mass, but for buildings that have the load capacity for intensive treatments and deeper soil media, an equilibrium assumption does not hold as well. This would increasingly be the case if relatively large volumes of water are present on the green roof since water adds significant mass and higher heat capacity to the roof. We apply the model to a non-green roof low mass structure, located at Penn State to test the equilibrium version of energy balance. We then use green roof data to study time delays due to the roof's greater mass.

Pennsylvania State University Field Data

The Penn State Center for Green Roof Research has developed and instrumented a green roof field experiment in central Pennsylvania. The experiment consists of six separate buildings, three with green roofs and three with control dark roofs (Figure 2). Each of the roofs and buildings are monitored for temperature, meteorological conditions and water retention and runoff. The waterproof membrane, drainage layer, growing medium and plants are identical for each green roof. The vegetation is *Sedum spurium*. Descriptions of the building structures and roofs are given in Denardo (2003).

Figure 3 shows averaged control rooftop surface temperatures and averaged green rooftop temperatures for the month of July 2003. The averages were calculated for all three buildings for both the control and green roofs. In addition, the data shown are hourly averages of temperature data taken every 5 minutes. For example, the noontime temperatures are the hourly average of 5-minute data collected between 11:00 am and noon. These data demonstrate the cooling potential of green roof surfaces compared to dark impervious surfaces. Peak temperatures can be 54˚F or more lower (equal to 30˚C lower) on the green rooftops.

Model Simulations

As a first application of the energy balance model we performed a simulation of the control rooftop temperature data shown in Figure 3. For this simulation we made estimates for the rooftop albedo and longwave emissivity based on their color and material composition. The thermal conductivity was known from the insulation material and dimension (Denardo, 2003). Latent heat was assumed to be zero for the control roofs.

With the exception of the convection coefficients γ_1 and γ_2 in equation A5 (see additional equations at the end of this study), all other model data were available either from the temperature data and meteorological recordings or from standard published literature. Therefore we treated the convection coefficients as unknowns to be determined by optimizing the model agreement with the measured rooftop temperatures. The optimization was made using the root-mean-square-error (RMSE) as the metric to be minimized. Figure 4 shows the best fit obtained by minimizing the RMSE.

Figure 4 shows that the model agreement with observations is excellent. This fit was obtained with values for γ_1 and γ_2 of 6.6 and 10.3, respectively. These values, combined with the varying windspeed data, imply total convection coefficients for (T_{roof}- T_{air}) term in equation A5 ranging from 10-22 W/m^2-K. While the available literature on such coefficients is sparse, this range agrees well with that reported by Berdhal and Bretz (1997) in their study of rooftop convection, in which they find a range of 18-25 W/m^2-K. Figure 4 uses hourly-averaged data for the solar forcing. When instantaneous data were used, the model

Figure 2. Green and control roof field experiment at Penn State University (Denardo, 2003).

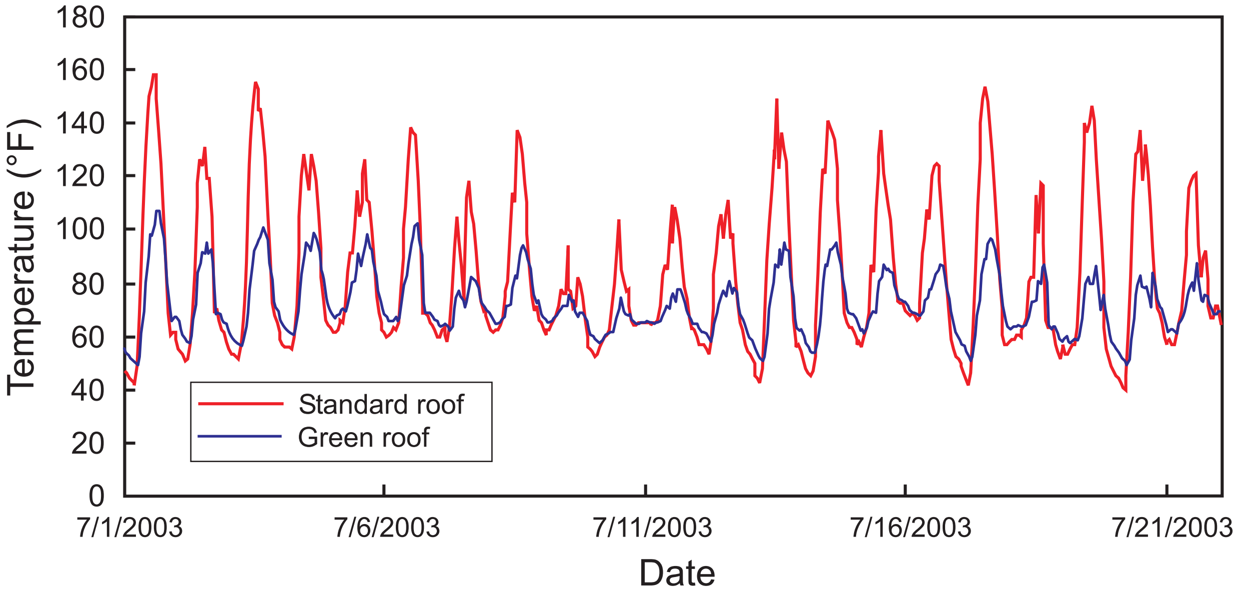

Figure 3. Average control and green rooftop surface temperatures observed on the Penn State University field experiment during July 2003 (Denardo, 2003).

shows short-term variability compared to the measurements. We interpret this to mean that the rooftop temperatures better reflect the average solar gain over the prior hour rather than the instantaneous gain due to thermal inertia effects.

The 'Equivalent Albedo' of Green Roofs Compared to White Roofs

With the control roof model thus calibrated, we pose a practical question for green roof research:

What albedo would be required on a white roof to reproduce the surface temperatures observed on the green roofs, as shown in Figure 3?

We refer to this albedo as the 'equivalent albedo' of green roofs. It combines in a single number both the latent and shortwave reflective cooling processes operating on green roofs (see Figure 1). It offers a simple way of comparing the cooling efficiencies of green and white roofs. If the equivalent albedo of green roofs is low compared to the albedo of white roofs, this could argue favorably for adopting white roofs as a mechanism for urban cooling. Alternatively, if the equivalent albedo is high compared to that achievable on white roofs this could argue favorably for green roof adoption.

To answer this question, we use the identical model parameters and meteorological forcing used for the results in Figure 4 but with the green roof surface temperatures as the target data and the albedo treated as an unknown to be determined by 'optimizing' the agreement.

We found that the model temperature cycles fluctuations preceded those of the green roof temperature by approximately one hour. We interpret this to be the effect of the increased mass and heat capacity of the green roof and retained water as compared to the control roofs. As a result, 'optimizing' the fit in this case is not a straightforward matter of minimizing the RMSE, because of the time lag between the simulated and observed temperature cycles. Nevertheless, we minimized the RMSE metric and found that a range of 'equivalent albedos' gave reasonably good fits that bracket the data. The degree of agreement varied over the month.

Figure 5 shows the model output with

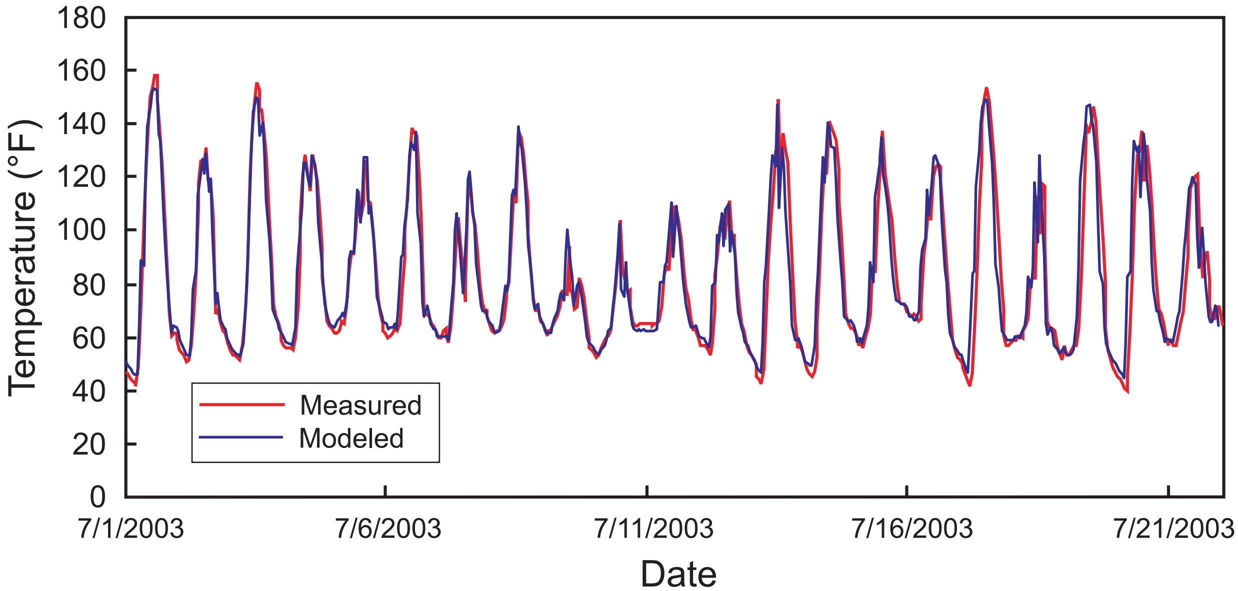

Figure 4. Modeled versus measured rooftop temperatures for July 2003 using hourly averages of 5-minute meteorological data, and adjusting the convection coefficients in equation A5 to minimize the RMSE measure of error.

the range of albedos that our model needed to bracket the data for the month of July. (The model data shown in Figure 5 are time-lagged by one hour for clarity. We estimate the equivalent albedo range to be between 0.7 and 0.85. Earlier in the month, the equivalent albedo of 0.7 matched the temperature peaks well while later in the month, this albedo made the model too hot. For the latter periods, an albedo of 0.85 cooled the model peaks in better agreement with the data. The physical reason for this variability likely has to do with the water status of the green roofs over the month. If more water is present at certain times, we expect the latent heat cooling to increase and thus elevate the equivalent albedo of the roof. We test this hypothesis in a follow-on study.

Discussion

The equivalent albedos found for the Penn State green roofs have implications for further green roof research. White or bright roofs are a competing technology to green roofs as a method to reduce the urban heat island and rooftop temperatures. The chief advantage of a white roof is that it is relatively inexpensive to install. But a key question that needs to be addressed is whether white roofs cool more effectively than green roofs? If white roofs do, this would be a second important advantage. The equivalent albedos found in this research provide an answer to this question.

Surface solar reflectivities in the range of 0.7 – 0.85 are among the brightest surfaces available from white coatings. Figure 6 shows reflectance (albedo) and longwave emissivity data for a number of standard building and rooftop materials (Florida Solar Energy Center, 2005). The albedo values are plotted on the horizontal axis and the corresponding emissivities are plotted on the vertical axis. White paint typically averages an albedo of 0.8, although maintaining high albedos on white surfaces is difficult. Without regular washing, the albedos of white surfaces rapidly drop due to natural weathering and soiling (Bretz and Pon, 1994). Albedo for white surfaces in outdoor environments have been reported to decline by an average of 0.15 over a year. In some cases, larger declines happen within

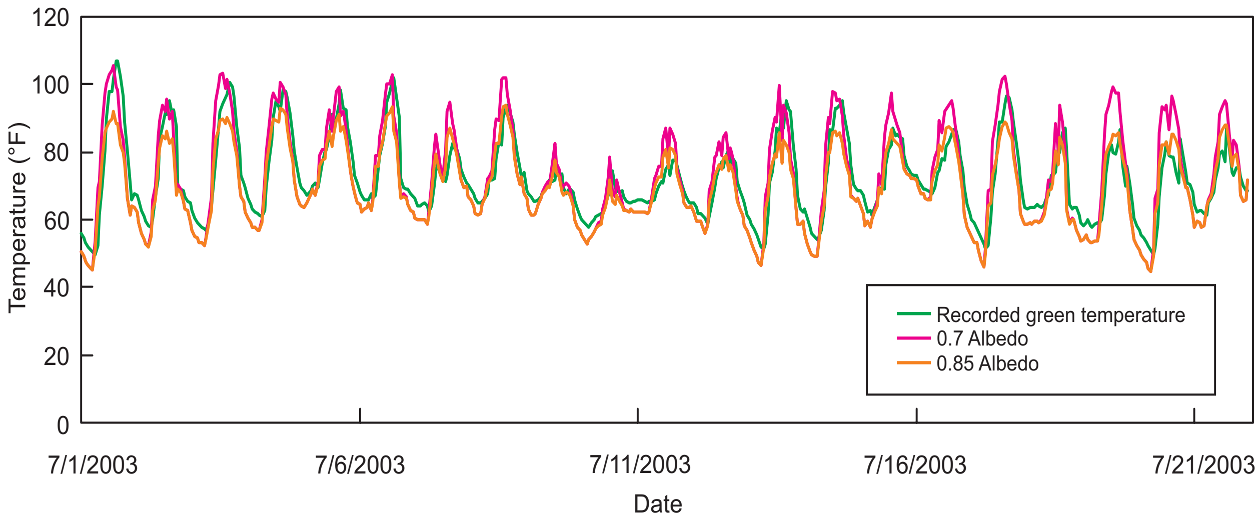

Figure 5. Simulation of the green roof surface temperatures using only a raised albedo (and no latent heat cooling) on the calibrated control roof model. A range of albedos (0.7-0.85) was needed to bracket the data. (Model data time-lagged by 1 hour.)

two months (Bretz and Pon, 1994). While the brightness can be restored by regular washing, the burden and costs of doing this one or more times a year would likely be a major deterrent to most building owners.

Green roofs, by comparison, are not cooling primarily through albedo, but through latent heat loss. Our equivalent albedo experiments suggest that they are cooling as effectively as the brightest-possible white roofs, but without the need for washing. There are other maintenance costs for green roofs, but for purposes of cooling, the maintenance may not be as intensive and burdensome. Green roof maintenance potentially may be an inviting and pleasurable activity for some building owners. In comparison, very bright white roofs with high glare tend to be harsh visual environments.

Although green roofs cool primarily through latent heat (along with a higher natural albedo compared to black roofs), our equivalent albedo experiment allows us to place green roof markers on Figure 5 for comparison to other materials. Vegetated surfaces have longwave emissivities in the range of 0.9 or higher (Oke, 1987), also among the highest for most materials. Combining that with an equivalent albedo of 0.7-0.85, green roofs are operating in the desirable upper left corner of the albedo-emissivity chart. For this data set at least, only one material (white plaster — not a rooftop candidate) has greater surface-cooling properties. This finding suggests that vegetation may be optimized by nature for cooling efficiency.

In this study we have used the green roof surface temperature as the target variable to be simulated by the equivalent albedos. With respect to the heat flow downwards into the room below, however, a more appropriate target would be the temperature observed at the conventional rooftop level below the green roof layer. It is this subsurface temperature which governs the heat flow into the room below, as given by equation A6. This subsurface temperature was monitored at the Penn State experiment and is significantly lower than the green roof surface temperature because it is insulated by the green layer above it. Using this subsurface temperature as the target for our equivalent albedo experiment would therefore require albedos even higher than the 0.85 needed for the surface temperature. Therefore the case can be made that green roofs are

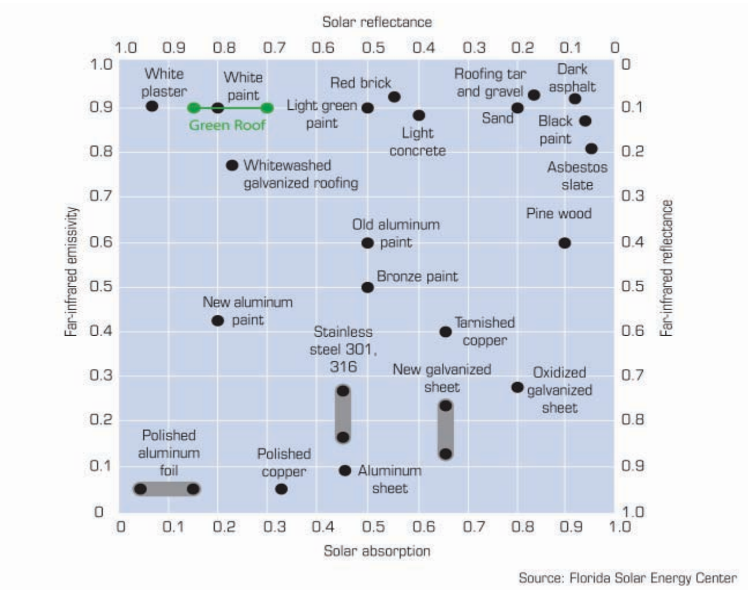

Figure 6. Data on solar reflectance (horizontal axes) and for infrared emissivity (vertical axis) for a number of common building materials (Florida Solar Energy Center). This study of green roof equivalent albedos allows us to hypothetically depict where green roofs lie in comparison to such materials (shown with the green bar using 'equivalent albedo' range of 0.7-0.85), with respect to cooling performance.

reducing heat flows into the building below to levels not achievable by white roofs.

Although green roofs are more expensive to install than white roofs, other benefits of green roofs besides temperature reduction could make them more desirable and cost-effective (Acks, this report). These other benefits include stormwater runoff mitigation, roof-service lifetime extension, building-amenity value and biodiversity value. White roofs, by comparison, offer only the one surface cooling benefit but this will require burdensome maintenance to be fully realized. In the same way that natural vegetated surfaces maintain themselves, a properly functioning green roof could be self-perpetuating with respect to cooling.

The 'equivalent albedo' concept is a practical metric that should be promoted in green roof and urban heat island research. To our knowledge it has not been introduced heretofore. This may be because its utility becomes clear only when comparing, as we do, two urban heat island strategies: vegetates surfaces and albedo increases. We encourage future energy balance studies to replicate the findings we report. We have only studied one field site, in one climatological regime, for an extensive green roof, with particular vegetation and during a limited time period. The varying drought and water status of other sites, climates, vegetation and seasons need to be considered and studied as well. The cooling efficiency of intensive versus extensive green roofs is another application for energy balance modeling to be explored in the future.

Additional Equations

Model Equations

Following are the equations we adopt for the seven energy fluxes depicted in Figure 1:

$$\text{Shortwave}_{down} = \text{Solar} + \text{Diffuse} \qquad \text{(A1)}$$

$$\text{Shortwave}_{up} = \alpha \cdot \text{Shortwave}_{down} \qquad \text{(A2)}$$

$$\text{Longwave}_{down} = (0.605+0.048 \cdot e^{½}) \cdot \sigma \cdot T_{air}^{4} \qquad \text{(A3)}$$

$$\text{Longwave}_{up} = \varepsilon_s \cdot \sigma \cdot T_{roof}^{4} \qquad \text{(A4)}$$

$$Q_{convection} = \gamma_1 \cdot u^{0.8}(T_{roof}-T_{air}) \text{ if } u>1.75, \quad \text{else}$$
$$= \gamma_2 \cdot (T_{roof}-T_{air}) \qquad \text{(A5)}$$

$$Q_{conduction} = \kappa(T_{roof}-T_{ceiling})/dz \qquad \text{(A6)}$$

$$Q_{latent} = \begin{cases} 0 & \text{for non-green roofs (e.g. standard, white)} \\ \dfrac{Q_{convection}}{\beta} & \text{for green roofs} \end{cases} \qquad \text{(A7)}$$

Following are brief definitions for the symbols: α = albedo, σ = Stefan Boltzmann constant (5.67.10-8 watts/meter^2-K^4), T_{air}= ambient external air temperature, e = water vapor pressure of the atmosphere, ε_s = longwave emissivity of the rooftop, T_{roof} = rooftop surface temperature, u = windspeed , α = thermal conductivity of the roof layer (Watts/m^2-K), $T_{ceiling}$ = interior ceiling temperature inside room below roof, dz = roof layer thickness, β = Bowen ratio of sensible and latent heat flux. All scientific units are metric in the model; temperatures are measured in degrees Kelvin, windspeed is in meters/second, radiation and heat flow terms are in watts/meters^2, and vapor pressure is in millibars.

Acknowledgements

We thank Daniel Hillel for helpful discussions on green roof energy-balance modeling.

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Potential Impact of Green Roofs on the Urban Heat Island Effect

William D. Solecki, Cynthia Rosenzweig, Jennifer Cox, Lily Parshall, Joyce Rosenthal, and Sara Hodges

Background

Urban heat island conditions are defined as elevated air and surface temperatures, most especially at night, in urban areas relative to surrounding suburban and rural areas. A heat island develops when heat-trapping built surfaces replace naturally vegetated surfaces that moderate temperature through evaporation from soils, transpiration from plants, and shading. These surfaces absorb shortwave solar radiation during the day and re-radiate it as longwave radiation during the night. The reduced vegetation of urban areas accentuates this process because the lack of shade exposes the absorptive surfaces to the sun's heating. The paucity of vegetative cover also limits the potential for evaporative cooling in comparison to the typically greener suburbs and rural areas.

Several potential urban heat island mitigation strategies are currently being reviewed by researchers to determine their relative effectiveness and cost efficiency. These include reflective surface material and increased vegetative cover (e.g., Sailor, 1995; Akbari et al., 2001; Solecki et al., 2005; Rosenzweig, Solecki, and Slosberg, 2006). In New York City, rooftops account for 19% of New York City's surface area, of which 11% are flat roofs, and a substantial portion of available open space. This study investigates whether adoption of green roofs could lower summertime surface temperatures and the heat island effect in New York City.

New York City's Urban Heat Island Effect

Heat islands in the greater New York metropolitan region have been studied by a number of authors (Gedzelman et al., 2003; Rosenthal et al., 2003; and Rozenzweig et al., 2004). Rosenthal et al. (2003) studied the historical development of the urban heat island effect in New York City, concluding that a heat island of at least 1.8°F (1°C) already existed at the beginning of the 20th century and that mean temperature at Central Park is currently 2.12–5.44°F (1.20–3.02°C) higher than at surrounding stations in the metropolitan region. Using a mesoscale network of weather stations installed in the five boroughs for the period 1997–1998, Gedzelman et al. (2003) found that New York City's heat island averages 7.2°F (4°C) in the summer and autumn and 5.4°F (3°C) in winter and spring (Gedzelman et al., 2003). Rosenzweig et al., (2004) used meteorological data to show that Newark, New Jersey's heat island averages 5.4°F (3°C) and Camden, New Jersey's heat island annually averages 2.7°F (1.5°C) (Rosenzweig et al, 2004).

The magnitude of the heat island effect in particular locations within New York City partially depends on surface properties (albedo, vegetation density, proximity to water, etc.) and urban geometry (building heights, road network, etc.) (Cox et al., 2004). Particular surface properties such as low albedo and low vegetation density can lead to surface heating and increase the potential for a heat island to develop. The average magnitude of the heat island in the city as a whole depends on surface heating as well as on synoptic-scale weather, season, and time of day.

Heat Island Mitigation Strategies

Although the urban heat island effect occurs throughout the year, its occurrence during the summer months is of public policy concern because of the environmental stress and health hazards associated with high urban temperatures in the summertime. The impacts of such conditions include increases in energy demand and emissions of carbon dioxide and other pollutants as well as enhanced air pollution and heat-stress related illness. Heat island impacts may be further amplified during summertime heat-wave conditions (Rosenzweig et al., 2004).

Two basic heat island reduction strategies are increasing surface reflectivity (albedo) and increasing vegetation density. The Heat Island Reduction Initiative (HIRI), a federal program that includes representatives from NASA, the US Department of Energy, and the US Environmental Protection Agency, promotes heat island reduction strategies including installing reflective, light-colored roofing and paving materials, planting shade trees, and increasing urban vegetative cover (Solecki et al, 2005). In addition, several states including California and Florida have developed heat island mitigation projects that assess the impact of reflective roofs and trees on the heat island effect (Solecki et al., 2005). In cities that have little available open space, green roofs could be a viable alternative and/or complement to adding vegetation at street level. In 2001, Tokyo mandated that all new mid-size buildings have a garden covering at least 20% of the roof (NYT, 2002). The Portland Bureau of Environmental Services is also evaluating green roofs as a heat island mitigation strategy; their preliminary calculations show that greening 100% of rooftops in one commercial/industrial neighborhood could reduce that neighborhood's heat island effect by 50-90% (Liptan et al., 2004).

Green Roof Functions

Green roofs cool the surface of the roof through evaporation from soils and transpiration from plants. The amount of cooling is primarily related to moisture availability and temperature. Green roof vegetation also shades the roof surface. While the relative contribution of each of these processes to cooling an urban environment is difficult to quantify with certainty, simulations suggest that the indirect cooling effect of evapotranspiration is greater than the direct effect of shading (McPherson, 1994).

Vegetation, especially in the presence of high moisture levels, plays a key role in the regulation of surface temperatures; perhaps an even stronger role than low-albedo surfaces (Goward, 1985). Further, studies show that increasing surface reflectivity and increasing vegetative cover have an approximately equal cooling effect (Bass, 2003).

A green roof simulation for Toronto found that converting 50% of Toronto's roof space into non-irrigated grassland reduced the city's summertime heat island of 3.6–5.4°F (2–3°C) by 0.2–1.4°F (0.1–0.8°C), with the distribution of green roofs and the actual magnitude of the reduction varying by neighborhood (Bass 2003). A simulation in which some of the roofs were irrigated produced a cooling of up to 3.6°F (2°C) in some neighborhoods (Bass, 2003; Akbari, 2002). The additional cooling can be attributed to enhanced evapotranspiration from the presence of irrigation water. Though the urban geometry of New York is different than that of Toronto, strategic implementation of green roofs may lead to similar levels of cooling.

Methods

Thermal satellite imagery was used to characterize surface temperatures associated with particular land-use classes in New York City. A single image corresponding to a hot summer day – when the urban heat island effect is likely to be of particular concern – was chosen for the initial work. Meteorological data were used to characterize heat island conditions for the same day.

The effect that replacing built surfaces with vegetated surfaces may have on average city-wide surface (skin) temperature was investigated using the satellite data, GIS data, and data from the Pennsylvania State University Center for Green Roof Research (Penn State). Ten percent and fifty green roof infrastructure scenarios were tested.

Characterizing Heat Island Conditions in New York City

A surface temperature map for New York City was developed using thermal satellite imagery. The image is from a Landsat ETM 7 acquired on August 14, 2002 at approximately 10:30 AM; the thermal band has a spatial resolution of 60 meters x 60 meters (Figure 1). Hourly meteorological data for Central Park, La Guardia Airport, John F. Kennedy Airport, and Westchester Airport in White Plains were obtained from the National Climatic Data Center (NCDC, 2004). These data were used to provide a general characterization of meteorological conditions associated with the satellite image and to determine the magnitude of the heat island effect in New York City on August 14, 2002.

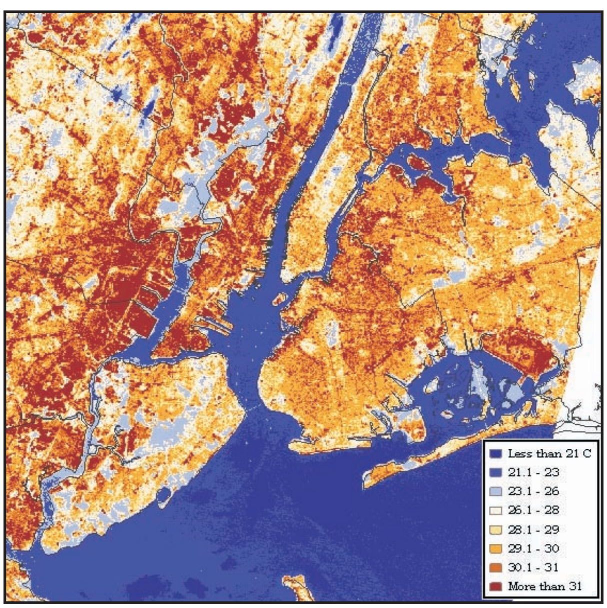

Figure 1. Thermal map of surface temperature in the New York metropolitan region. Landsat ETM 7, August 14 2002, 10:30 AM, Band 6.

Green Roof Infrastructure Scenarios

The impact of ten percent and fifty percent green roof infrastructure scenarios on average New York City surface temperatures were tested using several methods, each of which is described below. Scenarios for the Newtown Creek sewage-shed were also tested. Data on the total area of flat roofs within the city were provided by Hydroqual, Inc. In the case of Newtown Creek – which spans parts of Manhattan, Brooklyn and Queens – flat roof data broken down by borough were weighted and combined to produce an estimate of flat roof area in the Newtown Creek sewage-shed. For all methods, it was assumed initially that all flat roofs were available for green roof adoption; that every flat roof could hold a lightweight, *sedum*-based green roof; and that a sedum-based green roof would have approximately the same cooling effect as a grass roof. Because it is unlikely that the total area of any individual flat roof will be available for a green roof, it was further assumed that only 75% of the total flat area was available for greening. Finally, it is important to note that the spatial resolution of the satellite data was insufficient to resolve surface temperatures associated with street-level built surfaces from rooftop surface temperatures. The first two methods described assumed that there was no difference between the two. In the third method, rooftop surface temperatures based on the Penn State data were incorporated into the calculations.

(1) Simple four-class land cover classification using satellite data. Satellite data were divided into four land cover classes using a simple image classification (Table 1 and Figure 2). The average surface temperature of each class was calculated and the average surface temperature of the grassland class was taken as the surface temperature associated with a green roof. In other words, grassland served as a proxy for sedums. Temperatures for built surfaces were

Table 1. Four-class land cover classification for NYC and Newtown Creek based on satellite data.

Class	Area		Percent	Surface temperature	
	acres	km²	area	°F	°C
New York City					
Forests (tree cover)	10,034	41	5%	78.1	25.6
Grassland	75,579	306	39%	83.1	28.4
Built (paved & barren)	106,863	433	56%	85.4	29.7
Total	192,476	779	100%	84.1	29.0
Newtown Creek					
Forests (tree cover)	47	0.2	0%	79.4	26.4
Grassland	1,228	5	9%	84.4	29.1
Built (paved & barren)	12,735	52	91%	86.0	30.0
Total	14,010	57	100%	85.8	29.9

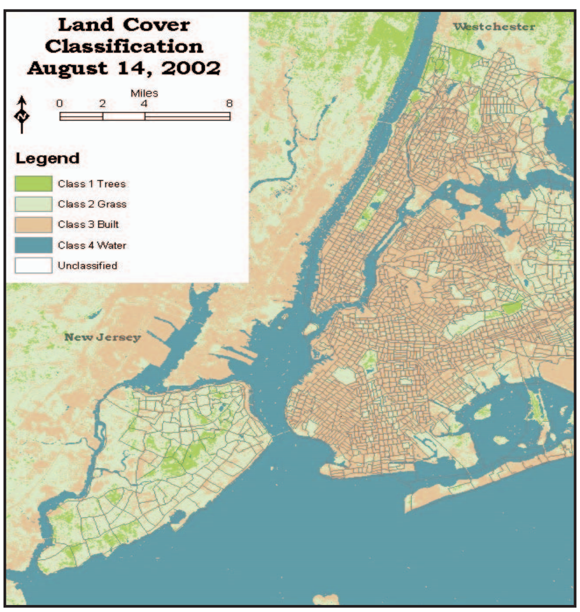

Figure 2. Land cover classification based on Landsat 7 image, August 14 2002.

replaced with temperatures for grassland and the effect on average surface temperature calculated according to Equation (1).

Average surface temperature

$$= \Sigma (A_i \cdot T_i)/A_t \qquad (1)$$

Where :

A_i = area of land cover class i

T_i = average surface temperature of land cover class

A_t = total area

(2) 1992 National Land Cover Dataset (NLCD) The existing twenty-two land class data set was modified to represent eight classes (Table 2). The final eight classes used consisted of water, grasslands/ pastures, forests, wetlands, and three urban categories (low residential, high residential, and commercial/industrial / transportation). This method allowed for a further breakdown of built classes. Average surface temperatures were again calculated according to Equation (1) with i = 8. Ten percent and fifty percent green roof infrastructure scenarios were applied first to a case in which the green roofs were distributed randomly across all three built classes and then in a case where the green roofs were only applied to the industrial/commercial/transportation class. Of the built classes, this was the class with the highest initial surface temperatures.

(3) Incorporation of Penn State data Given the 60 m x 60 m resolution of the satellite image, it was impossible to directly separate surface temperatures associated with street-level built surfaces from those associated with rooftops. However, given the results from analysis of Penn State energy data that showed average standard roof surface temperatures of 113.9°F (45.5°C), it seemed likely that using average built temperatures derived from the satellite image to represent average standard roof surface temperatures would lead to an underestimate of the base case temperatures used in the analysis (see Gaffin et al. in this volume). Therefore, Penn State data for average flat roof surface (roof membrane) temperatures were incorporated into the base cases by separating flat roofs from the built class. In the ten percent and fifty percent green roof infrastructure scenarios, Penn State data for green roof surface (i.e., top of the growing medium) temperatures were incorporated. An average of data from 10 AM and 11 AM over the month of July 2003 were used. These data were the closest match to August 14, 2002 available[1] .

Results and Discussion

The surface temperatures used in this analysis are derived from a satellite image acquired on August 14, 2002. This was a classic hot summer day in New York City with a pronounced urban heat island. Air temperature at Central Park had reached 91.0°F (32.8°C) by 11 AM, relative humidity was at 57%, and the sky was clear. Over the previous night, air temperatures in New York City had remained high as compared to temperatures in Westchester, with a peak difference of 7.9°F (4.4°C) between Central Park and Westchester at 2 AM and 9.0°F (5.0°C) between La Guardia Airport and Westchester at the same time (Figure 3). In the early morning, as temperatures rose, the gap was closed until at 11 AM the difference between Central Park and Westchester had dropped to 2.0°F (1.1°C) and the difference between La Guardia and Westchester had disappeared. Temperatures at Kennedy airport remained low as compared to other urban stations, likely because the Kennedy weather station lies on Jamaica Bay and temperature at Kennedy is moderated somewhat by sea breezes.

Given these clear, dry conditions, surface

Table 2. Post-classification land-use sorting based on eight National Land Cover Dataset (1992) classes.

Class	Area		Percent area	Surface temperature	
	acres	km²		°F	°C
Non-built surfaces					
Water	5,559	23	3%	78.5	25.8
Wetlands	4,696	19	2%	79.2	26.2
Forest	32,986	134	16%	81.4	27.4
Grass & pasture	5,283	21	3%	83.2	28.4
Barren (sand & gravel)	1,038	4	1%	84.6	29.2
Built surfaces					
Low residential	28,446	115	14%	83.8	28.8
High residential	93,278	378	47%	85.1	29.5
Commercial, industrial & transportation	28,849	117	14%	85.4	29.7
New York City Total	200,134	810	100%	84.0	28.9

1 The scenarios that incorporated Penn State data were not tested for Newtown Creek.

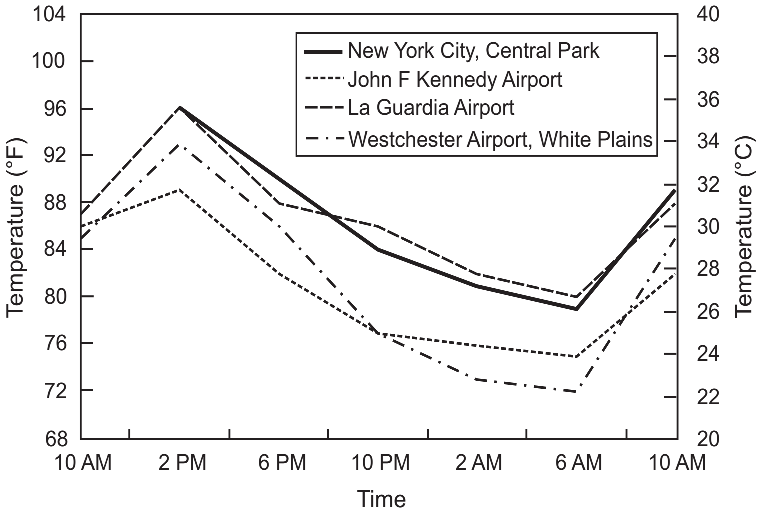

Figure 3. Diurnal temperature range August 13, 10 AM – August 14, 10 AM at meteorological stations in New York City and Westchester County.

Table 3. Results of greening scenarios using four-class land cover classification.

Case study	Surface temperature			
New York City	**°F**	**Diff °F**	**°C**	**Diff °C**
Base	84.1		29.0	
10% Green roofs	84.1	0.0	28.9	<0.1
50% Green roofs	84.0	0.1	28.9	<0.1
Newtown Creek				
Base	85.9		29.9	
10% Green roofs	85.8	0.1	29.9	0.0
50% Green roofs	85.8	0.1	29.9	0.0

temperatures rose quickly in the morning and average surface temperature city-wide was 84.1°F (29.0°C) at 10:30 AM. The difference between grassland and built surfaces was only 1°F (0.6°C). Therefore, when greening scenarios that replaced built surfaces with grassland were applied, the temperature reductions were negligible, even when the four classes were expanded to eight classes (Tables 3 and 4). Furthermore, even though Newtown Creek was hotter than New York City overall, a 50% green roof infrastructure produced no overall effect on Newtown Creek's average surface temperature.

These results are likely due primarily to the fact that ground surface temperatures and rooftop temperatures were lumped into a single class, and thus the higher rooftop temperatures were averaged with cooler ground surface temperatures, some of which were likely shaded. Additionally, because the Landsat sensor is at an angle, thermal data do not always correspond to flat exposed surfaces; rather some of the data likely corresponds to building walls and to shaded ground surfaces. Due

Table 4. Results of greening scenarios using National Land Cover Dataset classes.

	Surface temperature			
New York City green roof scenario	**°F**	**Diff °F**	**°C**	**Diff °C**
Base	84.0		28.9	
10% Green roofs, built classes	84.0	0.0	28.9	0.0
10% Green roofs, all industrial/commercial	84.0	0.0	28.9	0.0
50% Green roofs, built classes	83.9	0.1	28.8	0.0
50% Green roofs, all industrial/commercial	83.9	0.1	28.8	0.0

Table 5. Results using Penn State data for standard roof and green roof surface temperatures.

	Surface temperature			
New York City green roof scenario	**°F**	**Diff °F**	**°C**	**Diff °C**
Standard roof surface temperature	113.9		45.5	
Green roof Surface Temperature	76.5		24.7	
Four-class base case	87.3		30.7	
10% Green roofs	86.9	0.4	30.5	0.2
50% Green roofs	85.8	1.4	29.9	0.8
Eight-class base case	86.9		30.5	
10% Green roofs, built classes	86.8	0.1	30.4	0.1
10% Green roofs, industrial/commercial only	85.6	0.2	30.4	0.1
50% Green roofs, built classes	85.5	1.3	29.8	0.7
50% Green roofs,industrial/commercial only	85.5	1.4	29.7	0.8

to the complexities of the urban composite, other urban heat island studies have used high-resolution imagery such as ATLAS data to augment Landsat and other data (Quattrochi and Ridd, 1994). The acquisition of such imagery would likely improve the results.

When the Penn State data were incorporated and rooftop temperatures were separated from other built surfaces, there was a much greater reduction in surface temperatures (Table 5). With the 50% city-wide green roof infrastructure scenario, there was a reduction of up to 0.8°F (1.4°C). However, it is important to remember that the Penn State data were collected in July, 2003, but were used to supplement data for New York on August 14, 2002. Therefore, although the data may give a better sense of likely surface temperature reductions, the temperature reductions calculated here should be considered preliminary estimates that lay the basis for follow-on work.

One final point worthy of note is that there was a much greater difference between forest surface temperatures and built surface temperatures than between built surface temperatures and grassland which suggests that more intensive rooftop vegetation could produce greater cooling and reduction in the urban heat island effect than grassland or sedums. Our initial work has focused on sedums because they are hardy, drought-resistant plants that require only a thin layer of lightweight growing medium. Sedums are crassulacean acid metabolism (CAM) plants. While most plants open their stomata during the day to take in and fix carbon, these plants open their stomata at night. By keeping their stomata closed during the day, they are able to minimize water loss while using the carbon stored the night before. However, potential cooling from transpiration is minimized rather than maximized. Although sedums do keep the surface of the roof cooler (as seen by the Penn State data – Gaffin et al. in this volume) and evaporation from the growing medium also works to cool the roof surface, it may be worth considering other planting options in the context of green roof performance optimization.

Modeling the Effect of Green Roofs on Air Temperature and the Heat Island Effect

The work thus far has investigated the ability of green roofs to cool New York's surface temperature. In general, elevated urban surface temperatures create the potential for elevated urban air temperatures and a heat island to develop. The implication is therefore that if surface temperatures could be lowered by green roofs, air temperatures could be as well. This has been investigated directly with the Pennsylvania State University/National Center for Atmospheric Research regional-scale model (known as MM5 – website http://box.mmm.ucar.edu/mm5/; Grell et al, 1994) as part of the New York City Regional Heat Island Initiative (Rosenzweig, Solecki, and Slosberg, 2006). MM5 is a state-of-art, three-dimensional, non-hydrostatic, mesoscale model that has been used extensively at various resolutions for meteorological research applications running at NASA Goddard Institute for Space Studies at 36, 12, and 4 km resolution. The MM5 model has undergone sensitivity analysis in regard to calibration and operation in conjunction with observed data to yield realistic results. With the calibrated MM5 model, we simulate the effects of the surface properties (especially surface temperature) and meteorological variables on the surface temperature and the near-surface air temperature heat island effect. We then apply potential heat island mitigation scenarios including green roof infrastructure, street-tree planting, and light-colored surfaces. Scenarios are run for selected time periods that are representative of conditions when UHI effects are prevalent. The time periods selected depend on the spatial domain and resolution of the runs. In the future, the performance of green roofs as the climate changes will be modeled for the 2020s, the 2050s, and the 2080s.

Impacts of the Urban Heat Island Effect on Human Health

The higher temperatures created by the heat island effect in the New York metropolitan region are a concern because heat can be a health hazard. Excessive exposure to high heat can bring about injury or disease if the body is not able to cool down and shed excess heat (USDOHHS, 1992).

Less serious heat-related disorders include transient heat fatigue, heat rash, fainting and heat cramps. Heat exhaustion is a serious heat-related condition that can resemble the early symptoms of heat stroke. It is caused by the loss of large amounts of fluid by sweating, sometimes with excessive loss of salt. Heat stroke is the most serious acute heat-related disease, and results from the body's failure to dissipate heat. In heat stroke, the body's temperature regulatory system may fail with little warning to the victim. Body temperature is usually 105°F (40.5°C) or higher, and complications, brain damage or death often follow (USDOHHS, 1992).

Air pollution and heat stress are two important current public health stressors in many urban areas across the US, and both are strongly affected by temperature and climate variability. Extreme heat events endanger the health and well-being of elderly and poor urban residents. In New York, as in other cities around the world, summertime heat can lead to elevated mortality and morbidity rates, especially during the extended periods of hot weather known as heat-waves. Since 1998, summertime heat has been the top weather-related cause of mortality in the United States (NOAA 2001). Numerous epidemiology studies have examined the relationship between extreme heat events and increases in short-term mortality in urban populations in the temperate zone (Kalkstein and Greene, 1997; McGeehin and Mirabelli, 1999; Braga et al., 2002).

The epidemiological literature has identified factors in the built environment and demographic characteristics that can increase the risk of heat-related mortality. The elderly and people with pre-existing illnesses are particularly vulnerable populations; predisposing factors also include being bedridden, living alone, and having poor access to public transportation or air-conditioned neighborhood places (Semenza et al., 1996). Analysis of the Chicago 1995 heat wave, which led to over 700 excess deaths, showed that risk of heat-related mortality was higher in the black community, and in those living in certain types of low-income and multi-tenant housing, including living on the top floor of buildings (Klinenberg, 2002).

High spring and summertime temperatures can result in increased heat stress and higher daily mortality rates in New York City (Curriero et al., 2002). Public health researchers have estimated that there are presently over 300 heat-related excess deaths in New York City during an average summer (Kalkstein & Greene, 1997).

Indirectly, the higher temperatures associated with the heat island effect affect public health through increased ambient air pollutants. Higher temperatures accelerate the formation of harmful smog, as ozone precursors combine faster to produce ground-level ozone and have been shown to increase acute mortality rates, as well as increase hospital admissions for asthma and cardiovascular causes (Koken et al., 2003; Kinney, 1999; Thurston and Ito, 1999).

The higher temperatures caused by the urban heat island increase demand for cooling energy in commercial and residential buildings in summer increasing power plant emissions. Other air pollutants generated by power plants, such as particulate matter, carbon monoxide, sulfur dioxide and nitrogen oxides can also damage lung tissue, irritate lungs, and aggravate breathing problems, respiratory illness, and cardiovascular disease (Kinney, 1999; Amdur et al., 1991).

Possible municipal adaptive responses to protect vulnerable populations from heat-health effects include: access to air-conditioned places; use of heat and air quality health-alert systems; and environmental modifications that can provide an effective and passive approach for reducing the risk of heat stress (Smoyer et al., 2000). The benefits of green roof infrastructure in lowering ambient air temperature and reducing indoor temperatures in residences lacking air conditioners should provide a beneficial intervention for protection of public health from heat and air quality-related health impacts.

Conclusions

Green roofs could be an important urban heat island mitigation strategy for New York City. Green roof infrastructure could reduce average surface temperatures in New York City by as much as 1.4°F (0.8°C) if 50% of the city's flat roofs are greened. This could lead to a reduction in the city's urban heat island effect, and could improve air quality and public health in the city.

Further Research

Further research is needed to determine the direct impact of green roof infrastructure on New York City's summertime air temperatures and heat island effect. In particular, use of the MM5 mesoscale model allows for characterization of the city's heat island with and without green roofs. Additional research should include comparison of different green roof systems (extensive, intensive, irrigated, non-irrigated) as well as the impact of different green roof distributions (neighborhood clusters v. randomized distribution) and the impact of green roofs placed on different building types of different heights.

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Hydrologic Functions of Green Roofs in New York City

Debra Tillinger, Gary Ostroff, David Beattie, Robert Berghage, Paul Mankiewicz, and Franco Montalto

Background

Highly developed urban landscapes are less pervious to water than undeveloped areas. During storms, well-vegetated areas moderate the intensity and quantity of stormwater runoff within a watershed. The velocity of rainfall striking the ground is reduced by trees and other vegetation. Water intercepted by tree canopies is quickly evaporated back into the atmosphere while water on the soil is absorbed, as if by a sponge, to be released slowly into local streams. In a heavily urbanized area, rain falls with full force onto the ground, runs off from paved or impervious surfaces almost immediately, and little area is available for recharge into the local groundwater. The net effects of urbanization can be flooding, and in areas that are served by combined sewers, the discharge of dilute sewage into local waters.

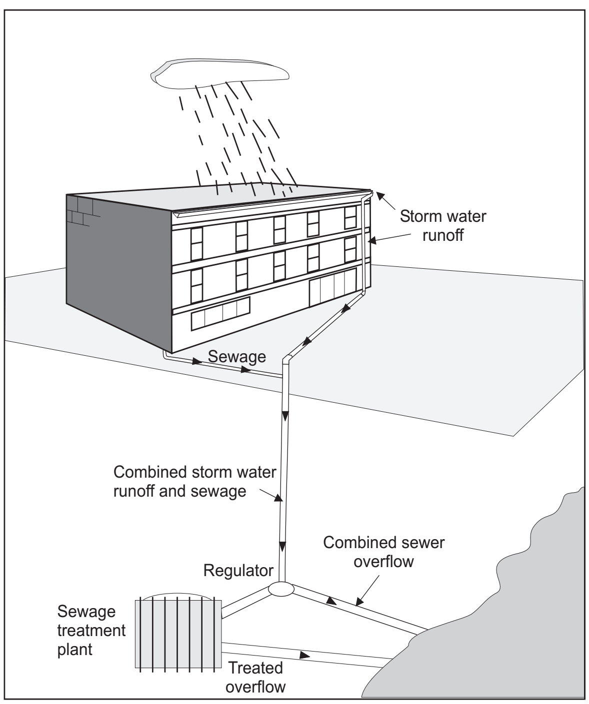

Figure 1. Combined sewer system. Note the regulator, which allows combined sewer overflows (CSOs) to occur when there is too much rain for the wastewater treatment plant to handle.

Combined sewer overflows (CSOs) occur when sewage and stormwater are discharged from sewer pipes without treatment. CSOs are a significant source of environmental pollution in New York, where approximately 80% of the city functions on a combined sewer system (Protopapas, 1999) and only ~60% of rainfall is collected and treated (NYCDEP, 2001). In a combined sewer system, sewage and stormwater flow through the same pipes to wastewater treatment plants (Figure 1). Each wastewater treatment plant serves an artificial drainage basin known as a sewage-shed; in New York City there are 14 sewage-sheds of varying size. Total capacity is 1.8 billion gallons and total dry weather flow is 1.5 billion gallons per day.

During dry weather, all sewage is treated before it is discharged from the treatment plant to the estuary. However, during wet weather, the amount of water in sewer pipes may increase 10 or 20-fold. To prevent this increased volume of water from overwhelming treatment plants, a regulated amount (twice the average dry-weather flow) is directed to the plants by regulators that intercept sewage at all major CSO discharge points. The balance of the dilute sewage is discharged to local waters.

Underground storage tanks are an example of an engineering approach that retains CSO discharge flows for later re-introduction to the sewer system. Other engineering approaches seek to redress the hydrologic balance of urbanized areas by restoring or replacing some elements of the natural system. These approaches, some of which are known as Low Impact Development, increase the permeability of areas in a sewage-shed so as to delay or prevent stormwater from discharging immediately to the sewer system.

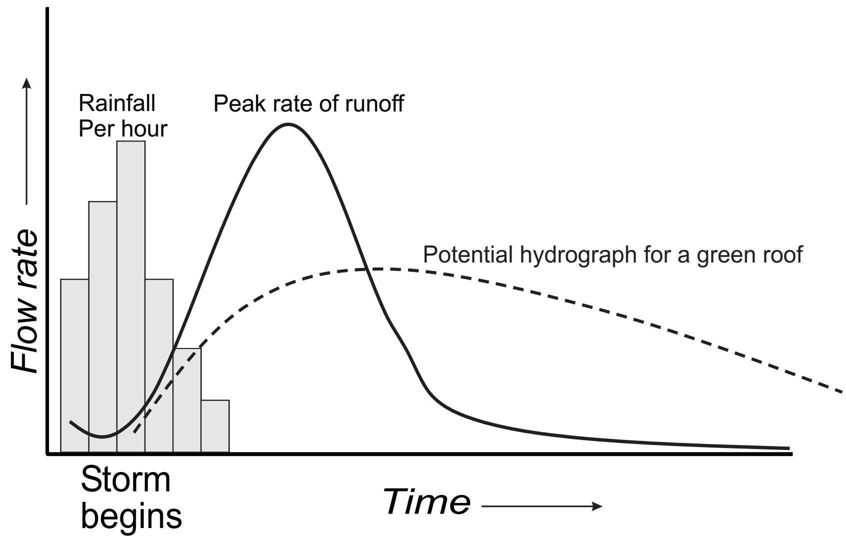

Figure 2. Hydrograph comparing hypothetical runoff from a standard roof to runoff from a green roof.

A 1999 report to the NYC Department of Environmental Protection (DEP) stated that vegetated roofs could have significant feasibility as an alternative to storage-tank technologies in some wastewater drainage basins (Copp et al., 1999). Modeling studies in Vancouver, BC; Seattle, WA; and Portland, OR have investigated this potential (Graham and Kim, 2003; Liptan et al., 2004; Taylor and Ganges, 2004. This study evaluates potential green roof hydrological functions through data analysis and modeling to determine whether green roofs could have an impact on the frequency and severity of combined sewer overflow events in New York City.

Green Roof Functions

Green roof infrastructure could benefit New York City by absorbing and later evaporating stormwater as well as retarding its flow. The overall effect would be a reduction in the amount and rate of discharge of stormwater into the combined sewer system, thus potentially reducing the frequency and volume of CSO events. Even small reductions in flow may have benefits that are much larger than expected to the extent that they reduce peak rates and flow volumes responsible for much of the flooding and CSO events.

Studies have shown green roofs to be effective at capturing rainfall. For example, the city of Portland found that a green roof with a 4 – 5 inch (10 – 13 cm) growing medium and 72% plant cover of mixed succulents could absorb 69% of the annual rainfall that fell on it (Hutchinson et al., 2003). During summer storms, the roof retained 100% of the rainfall, and peak runoff rates were significantly lower for the green roof than for a control roof. For a theoretical discussion of water relations on a green roof, see Appendix I.

The ability of green roof infrastructure to function as a stormwater catchment system depends on a number of factors including type of green roof (intensive or extensive), soil type, plant type, severity of a particular storm, and antecedent weather. The design of a green roof system needs to optimize both hydrological and structural functionality. For example, the

Figure 3. Case study areas.

lightweight, soil-like growing media used on extensive green roofs are designed to minimize load on weight-bearing roof structures, while still absorbing and storing rainwater. Choice of plant type also affects these functions. A common current choice for extensive green roof plants are desert-adapted stone crops (sedums), capable of withstanding both heat and drought. These plants are succulents, meaning that they have a high plant water-holding capacity; furthermore, they open their stomates at night to reduce evaporative losses (Raven et al., 1992).

While very heavy storms (e.g., several days of continuous rainfall) can lead to saturation and diminish the ability of green roofs to capture rainfall, rainwater still percolates through the green roof system before entering the sewer system, creating a moderate delay between peak rainfall and peak runoff from a green roof (Figure 2). Conversely, a prolonged drought could lead to soil compaction and reduction in green roof functionality. However, such compaction is less likely in the case of green roof soils than in regular soils, because green roof soils generally consist of large grains with many internal air spaces.

Climate Change

Global climate change presents significant challenges to the New York metropolitan region. Sea-level rise and accompanying increases in coastal storm flooding have been identified as a key vulnerability of the region (Rosenzweig and Solecki, 2001). Local tide-gauges show that sea-level is already rising, due in part to geological processes and in part to recent anthropogenic warming (Gornitz, 2001). Global warming and its accompanying projected rise in sea level are likely to lead to increases in the flooding damages that accompany coastal storms (Zhang et al., 2000; Senior et al., 2000; Gornitz, 2001). Individual rain events are also expected to increase in intensity (IPCC, 2001). Thus, the frequency of CSO discharges may rise as rising sea levels diminish the sewers' conveyance capacity, while rainfall intensity grows.

Methods

Rainfall and runoff data from the Pennsylvania State University Center for Green Roofs Research (Penn State) were analyzed to determine the extent to which extensive green roofs are capable of capturing rainfall that would otherwise run off into the sewer system. The site is approximately 250 miles west of New York.

The data analysis was complemented by development of a simple simulation model (NYGRM/Hydro) that was used to conduct experiments regarding the impact of green roof infrastructure on stormwater runoff at the sewage-shed scale in NYC. A range of green roof performance inputs were tested, including those corresponding to the results of the data analysis.

The model was used to simulate captured runoff for two case studies, the Newtown Creek and North River sewage-sheds (Figure 3). Newtown Creek is the largest sewage-shed in New York City and includes parts of Manhattan, Brooklyn, and Queens. Upgrades to increase this plant's current capacity of 310 million gallons per day are being planned. The North River wastewater treatment plant serves Manhattan's West Side including Columbia University. The North River sewage-shed is approximately half the size of Newtown Creek, but has the same percentage of land surface area covered by flat roofs. The capacity of North River's treatment plant is 170 million gallons per day.

Data Analysis

The Penn State experimental design consists of six identical small buildings, three with standard roofs and three with extensive green roofs. The green roofs have a drainage layer, a 3.5 inch (8.89 cm) layer of expanded clay-based mineral substrate, and a mix of *Sedum spurium*, *Sedum album*, and *Delosperma nubigenum*,

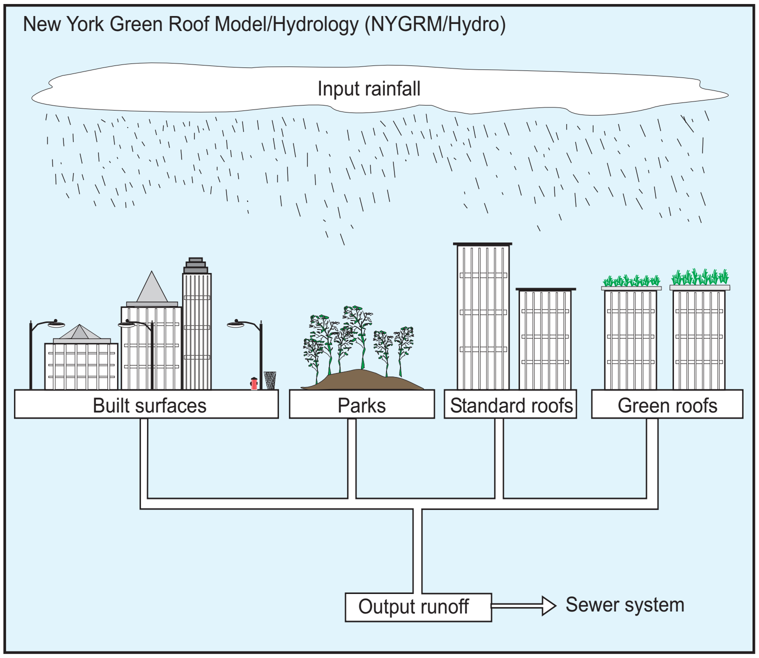

Figure 4. New York Green Roof Model/Hydrology (NYGRM/Hydro). Rainfall is the input and stormwater runoff is the output.

covering 90-100% of the surface. Each building is equipped with an enclosed gutter connected to a barrel with a pressure transducer to sense rainfall volume at 5-7 minute intervals . The experimental design also includes a weather station to collect meteorological data including rainfall at 5-minute intervals. Penn State data for June 2003 – September 2003 were used. Matched pair t-tests with unpooled variance were used to verify a significant difference at the 99% level between runoff from the standard roofs and runoff from the green roofs. Data from the three green roofs were averaged together, as were data from the three standard roofs.

Average captured runoff Average captured runoff (or retention) was defined as rainfall that makes direct contact with the roof but does not drain from the roof. It was calculated according to equation (1). Percent captured runoff (percent retention) was calculated according to equation 2.

Average captured runoff =

$$\left[\sum_{i=1}^{n}(R_i \cdot r_i)\right]/n \qquad (1)$$

Captured runoff =

$$\sum_{i=1}^{n}(R_i \cdot r_i)/\sum_{i=1}^{n} R_i \qquad (2)$$

Where R_i = total rainfall for event i
r_i = total measured runoff for event i
n = total number of rainfall events

Average captured peak runoff Because the green roof system retards (detains) the flow of stormwater, there can be a significant lag between the time a raindrop makes contact with the roof and the time it enters the sewer system. This is particularly important from a CSO reduction standpoint because it delays the time of peak runoff from the green roof. Peak rates of rainfall were computed based on the highest volume of rainfall that occurred in any five-minute period during each rainfall event.

Table 1. Baseline data for North River and Newtown Creek sewage-shed case studies.

Component	**North River areas**			**Newtown Creek areas**		
	(acres)	(km2)	(%)	(acres)	(km2)	(%)
Built surfaces	2,023	8.19	51	5,403	21.86	63
Parks	773	3.13	20	744	3.01	9
Standard flat roofs	1,135	4.59	29	2,451	9.92	29
Green roofs	Depends on greening scenario.					

Table 2. Performance assumptions and reservoir heights used in the box model. The Penn State scenario for flat roof and green roof rainfall capture correspond to results of the data analysis.

	Performance scenario (% rainfall captured)				Reservoir height	
Component	**Low**	**Medium**	**High**	**Penn State**	**inches**	**cm**
Built surfaces	2	2	2	2	0.04	0.1
Parks	80	80	80	80	1.57	4.0
Standard flat roofs	2	2	2	24	0.20	0.5
Green roofs	20	50	80	80	0.98	2.5

Note that the peak rainfall and the peak runoff for each roof may occur at different times.

Factor analysis The data were also analyzed using multiple linear regression to determine the degree to which the amount of runoff captured depends on the amount of rainfall and event duration, as well as antecedent conditions such as inter-event interval (measured in number of hours elapsed since the end of the previous rain event). Meteorological factors including relative humidity, solar radiation, and windspeed were also compared to runoff rates. For each of these factors, three-day averages were used. The meteorological variables were used as proxies for soil moisture, since soil moisture was not measured directly due to the incompatibility of soil moisture probes with green roof growing media. A determination of which factors best predict green roof retention capabilities can help to predict the hydrological effects of a severe storm in an area with green roofs with more accuracy.

New York Green Roof Model/ Hydrology (NYGRM/Hydro)

To determine the effect of green roofs on New York City hydrology, a simple green roof infrastructure stormwater model (New York Green Roofs Model/Hydrology (NYGRM/ Hydro)) written in the C-sharp programming language was developed to simulate rainfall-runoff relationships at the sewage-shed level (Figure 4). The model treats the sewage-shed as a large box filled with smaller compartments. Using GIS data, the land area within each case study was divided into built surfaces, parks, standard flat roofs, and green roofs (Regional Plan Association) (Table 1). Built surfaces include streets and structures without flat roofs.

Daily rainfall data from Central Park, NYC for 1984 (a wet year) and 1988 (a normal year) were used to drive the model. Total rainfall in 1984 was 57 inches (145.02 cm), and total rainfall in 1988 was 45 inches (113.53 cm). The model distributes rainfall among the compartments based on the percentage of the sewage-shed's total land area occupied by that compartment. The distribution of each compartment's total area is not considered, nor are edge or splatter effects.

The model was run with three greening scenarios – 0% (base case), 10%, and 50% adoption of green roofs in the sewage-sheds – and four roof performance scenarios (Table 2). The performance scenarios vary assumptions about the ability of standard flat roofs and green roofs to capture runoff. The high scenario uses green roof retention based on our Penn State findings (80% runoff-capture rate), but assumes that standard-roof retention is the same as built-surface retention. The medium scenario is in line with other studies that report green roof capture of approximately 50% of rainfall.

Each performance scenario assigns each compartment a unique homogeneous water-holding capability. Each compartment is also assigned a reservoir height that specifies the maximum depth to which water can fill. This means that each compartment has the capability to retain some percentage of water, but there is a finite total amount that can be held. Once a compartment is saturated with water, the percent runoff captured falls to zero. (Evaporation was incorporated indirectly by programming each reservoir to empty after two days.)

The model calculates the total annual runoff for the sewage-shed. Percentage reductions in total annual runoff were calculated by dividing output for the greening scenario by output for the base case for each performance scenario and each year.

The performance scenario inputs are approximations because the ability of any surface to retain water is partially based on antecedent conditions. The ability of a surface to hold water gradually decreases as it becomes more saturated, as opposed to the sudden drop to zero absorption in the model. Furthermore, it is clear that all members within a single category will not retain water in precisely the same manner. However, the simulation experiments with the model can suggest the way parts of the system may behave in different rain events.

Results

Data Analysis

Analysis of the Penn State data showed that green roofs are effective at capturing (retaining) rainfall during rainstorms (Figure 5). On average, the green roofs captured 80% of the rainfall (Table 3). A hydrograph for runoff during a typical rain event at Penn State is shown in Figure 6. Between June and September 2003, the green roofs captured more rainfall than the

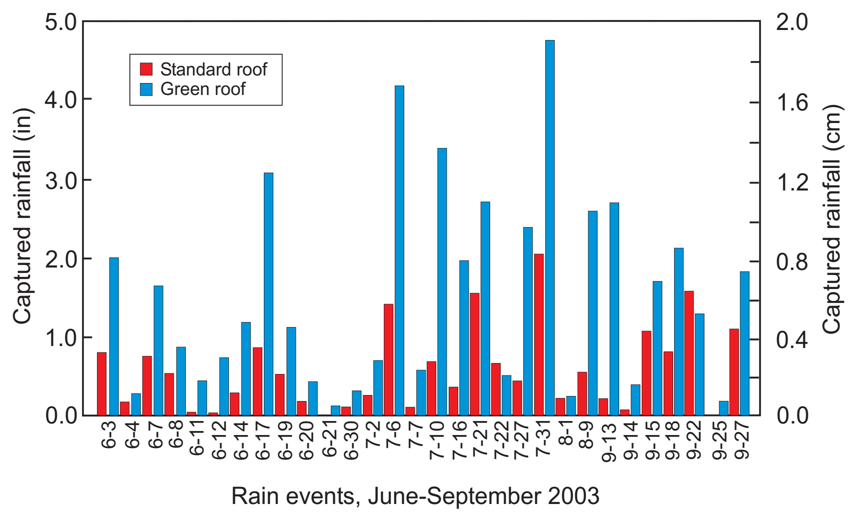

Figure 5. Captured runoff, June–September, 2003.

Table 3. Captured runoff as a percentage of rainfall on standard roofs and green roofs at Penn State Center for Green Roofs Research, June–September, 2003.

Captured runoff	**Standard roof**		**Green roof**	
Average runoff captured (% of rainfall)	24		80	
Peak runoff captured (% of rainfall)	26		74	
Captured runoff (inches and cm)	inches	cm	inches	cm
Average runoff captured	0.22	0.57	0.58	1.49
Peak runoff captured	0.03	0.08	0.06	0.16
Peak runoff extremes (inches and cm)				
Maximum peak runoff	0.18	0.46	0.11	0.27
Minimum peak runoff	0.01	0.02	0.00	0.00

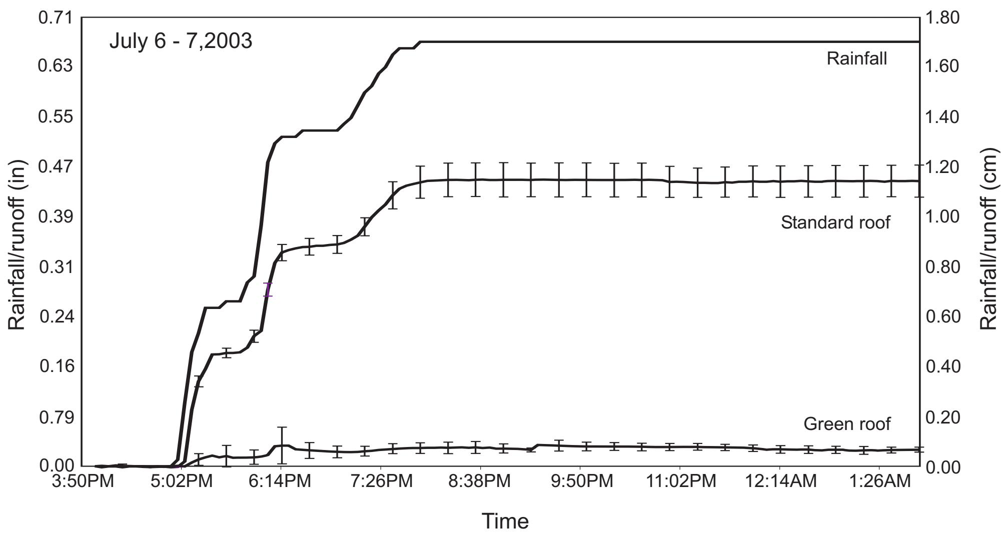

Figure 6. Simulated runoff, July 6–7, 2003.

standard roofs during all but two of the rain events and in these two cases, the difference was 0.04 inches (0.1 cm) or less. A comparison of standard roof runoff minima and green roof minima showed that the standard roofs always had at least a small amount of runoff, whereas the green roofs sometimes had no runoff. At peak times, the green roofs captured 74% of the rainfall.

The factor analysis showed that total rainfall is the best predictor of captured runoff for a rain event. Adding inter-event interval, peak rainfall, and a three-day solar radiation average improved the adjusted r^2 from 0.45 for rainfall alone to 0.56 with the inclusion of the additional factors. Predicting runoff capture as a percent of total rainfall was more difficult. The adjusted r^2 for rainfall alone was 0.34; adding additional factors produced an r^2 of 0.52. Equations (3) and (4) show the final multiple regression equations.

Captured runoff (inches or cm) =

$$0.243 \cdot R + 0.002 \cdot i + 0.128 \cdot p + 0.002 \cdot s - 0.230 \quad (3)$$

Captured runoff (percent) =

$$-0.123 \cdot R + 0.002 \cdot i - 0.004 \cdot d - 0.011 \cdot h + 1.64 \quad (4)$$

Where R = total rainfall (inches or cm)
i = inter-event interval (hours since end of previous rain event)
p = peak rainfall (highest 5-minute rainfall volume during event)
s = solar radiation (three-day average watts/m2)
d = event duration (hours)
h = relative humidity (three-day average %)

NYGRM/Hydro Simulations

Simulations showed that green roofs could reduce annual stormwater runoff at the sewage shed level by as much as 10% in North River and 9% in Newtown Creek with 50% green roof infrastructure (Table 4). For both case studies, 10% green roof infrastructure produced at most a 2% reduction in runoff from the base case. In general, increasing the infrastructure from 10% to 50% reduced runoff by as much as 8 additional percentage points for the high performance scenarios. Changing from a low performance scenario to a high-performance scenario reduced runoff by as much as 7 additional percentage points. The simulations consistently showed differences of less than 0.5% between the wet year and the normal year,

Table 4. Model results for North River and Newtown Creek sewage-sheds using Central Park meteorological data for 1988 (normal year) and 1984 (wet year) with 10% and 50% greening scenarios. 0% represents the base case with 0 green roofs.

Runoff (% of base)	**North River 1984**			**North River 1988**			**Newtown 1984**			**Newtown 1988**		
Greening Scenario →	**0%**	**10%**	**50%**	**0%**	**10%**	**50%**	**0%**	**10%**	**50%**	**0%**	**10%**	**50%**
Performance Scenario												
Low (%)	100	99	97	100	99	97	100	99	97	100	99	97
Medium (%)	100	99	93	100	99	93	100	99	94	100	99	94
High (%)	100	98	90	100	98	90	100	98	91	100	98	91
Penn State (%)	100	98	92	100	98	92	100	99	93	100	99	93

with slightly better performance in the normal year. Overall, the effect of green roofs was slightly more pronounced in retaining runoff in North River than in Newtown Creek.

Discussion

Analysis of Penn State data showed that extensive green roofs are effective at capturing rainfall. The green roofs captured 74% of the peak rainfall, implying that green roofs can reduce the sudden influx of water that causes CSOs. A green roof, in effect, acts as capacitor for the sewer system, dispensing water at a moderated rate that presents less strain to the design of the system and fewer opportunities for overflow.

The data also showed that standard roofs captured 24% of rainfall on average, although the small Penn State roofs may be subject to larger edge effects, with the likely result that water is splattering over the sides of the roofs rather than being captured. There should be comparatively less splatter from the green roofs because the soil medium is absorbent. A runoff capture rate of 80% for the green roofs is still possibly an overestimate. On the other hand, summer 2003 was a particularly wet summer in Pennsylvania, suggesting that the green roofs performed well when needed most and that their performance might be even better in less wet years.

Green roofs are complex systems with varying capacities for retaining rainwater and retarding runoff. When a range of capture rates (including 80%) was tested in the NYGRM/Hydro model, the box model results indicate that extensive green roofs can retain up to ~10% of annual rainfall at the sewage-shed scale, given the 50% adoption rate. Depending on the pattern of rainfall and the volume of runoff required for a CSO to occur, small reductions in runoff could translate into larger CSO reductions.

Conclusions

The research presented indicates that green roofs, as a means of runoff source prevention, show promise for reducing the frequency of CSO discharge in urban areas like New York City. Our data analysis and model simulations showed that green roofs have the potential to be effective in reducing runoff at the individual building and sewage-shed scales. The research also indicates that a significant percentage (~50%) of roofs in a sewage-shed would need to be greened to significantly lower the frequency and severity of CSO events. Analysis of the Penn State data showed that individual extensive green roofs can capture up to 80% of rainfall. Simulations of the impact of green roof infrastructure in New York indicated that 50% green roof infrastructure in a sewage-shed could produce up to a 10% reduction in runoff. Therefore, it appears that, if adopted at the sewage-shed scale, green roof infrastructure could potentially provide an effective stormwater catchment system and could help to prevent combined sewer overflow events.

As climate changes and sea level continues to rise, low-lying storm sewers may have increasing trouble discharging CSOs, with the possibility of combined sewage backing up in pipes and rising to street level. The development of effective stormwater catchment systems, such as green roofs at the sewage-shed scale, is therefore of particular importance in coastal areas such as New York City that are likely to be affected by climate change.

Further Research

Understanding the role of environmental factors in green roof performance is needed in order to optimize their water-retention capabilities based on the region's climate. We recommend that further research be conducted to determine more accurately the potential impact of green roof infrastructure on combined sewer overflow events in New York City. This additional research would involve collection of better data regarding both the within-hourly distribution of rainfall occurring in this region and the type of rainfall events that cause CSO discharge in each of the City's sewage-sheds and sub-sewage-sheds. More data also need to be collected quantifying the rates of runoff generated on green roofs of different sizes and configurations under rainfall events of different intensities and duration.

More detailed hydrologic models could then be used to establish more precise estimates of the extent of green roofs that would potentially need to be introduced to the urban landscape to achieve quantifiable reductions in CSO discharge. The NYGRM/Hydro simulates runoff, not reduction in CSO volume; more complex models are needed to simulate the impact of green roofs on CSO volume directly. The EPA SWMM model, in combination with local data on green roof performance, is one model that might be used to begin to directly address the relationship between green roofs and CSO events (Figure 7). The SWMM model has the advantage of a more direct inclusion of evaporation as well as the ability to treat each regulator basin individually and then to aggregate up to the sewage-shed scale. The modeling effort could include refining inputs, evaluating the performance of a range of green roofs including both extensive and intensive systems, and testing the sensitivity of the model to different performance inputs and antecedent conditions.

Further research could also usefully explore the potential for other runoff source prevention techniques (e.g., rainwater harvesting, stormwater infiltration, etc.) as ecological infrastructure.

Acknowledgements

Amir Burbea at Rutgers University kindly helped to program the model and also hosted it on his webspace.

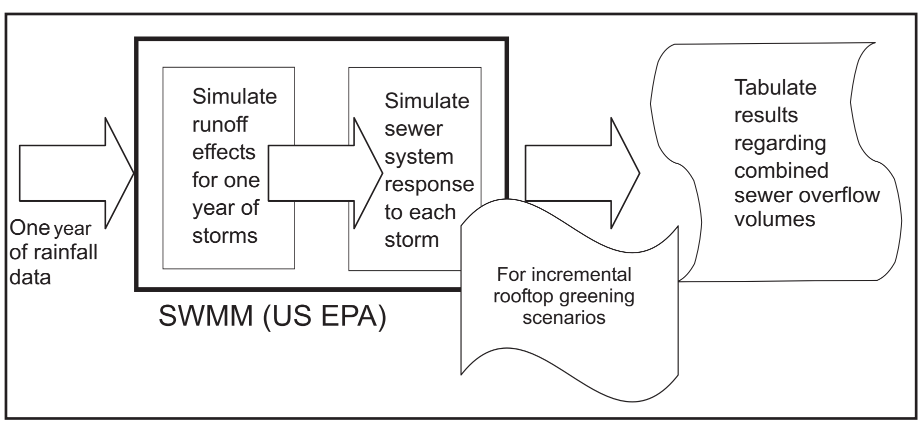

Figure 7. Diagram of
green roof simulations with the EPA Stormwater Management Model

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Green Roof Research Station: Rationale, Experimental Design, Equipment, and Estimated Costs

Cynthia Rosenzweig, Daniel Hillel, and Lily Parshall

A central component of our work is the development of a rooftop research station to collect data about green roof performance in New York City. The overall objective is to understand and document how green roofs function in New York. A specific goal is to gather applicable data from a rigorously instrumented site in New York to calibrate and validate our energy-balance and hydrology models over a range of weather and climate conditions. Other goals include developing a monitoring protocol to be shared with other green roof projects in order to facilitate characterizations and comparisons of green roof performance around the city and studying other aspects of green roofs such as their effects on biodiversity, air quality, and real-estate amenity values. The Green Roof Research Station would also provide educational opportunities for students at all levels, with a particular focus on high school and college-level research projects and theses.

The interaction of models and observations is a crucial component of the research design. It allows each sector to obtain results specifically applicable to New York City, and it also allows us to address complex cross-sector questions, such as the energy and water relations of a green roof.

Site Selection and Green Roof Construction

The first step is to select an appropriate research site – one that is accessible, not excessively shaded, and structurally sound. A structural engineer evaluates the proposed site and reviews plans to ensure that installation of a green roof does not threaten the integrity of the existing roof, and that the experimental equipment does not cause stresses such as areas of freezing that may block drainage. We then work with a leading green roof manufacturer to select a waterproof membrane, green roof system, substrate, and vegetation (Table 1). For our initial experiments, lightweight, industrial-type configurations are likely to be chosen. The vegetation would likely include *sedums* and/or similar plants, which are drought-resistant, low-maintenance, hardy, and able to survive in a thin and lightweight growing medium. Follow-on work would include intensive plots with a wider array of vegetation.

Table 1. Green roof system components and estimated costs per square foot.

Green roof construction	Cost per sq. ft.
Green roof system	\$5-10
Waterproof membrane	\$10-15
Plants	\$1-3
Installation labor	\$3-8
Maintenance (per year)	\$1.50-2
Construction Total	\$20.50-38

*Additional costs could include structural engineering assessment, architecture and engineering services, and electrical and plumbing work to connect to monitoring equipment.

Experimental Design

Our experimental design for the research station requires a minimum of 3 green plots and 1 control plot, all with equal area (Figure 1). This design allows for comparison between a green roof and a standard roof as well as between two different substrate depths and two different plant mixes. It also allows us to run our models with different green roof configurations to determine the sensitivity to changes in variables – for example, soil depth or plant type.

The research station would be equipped

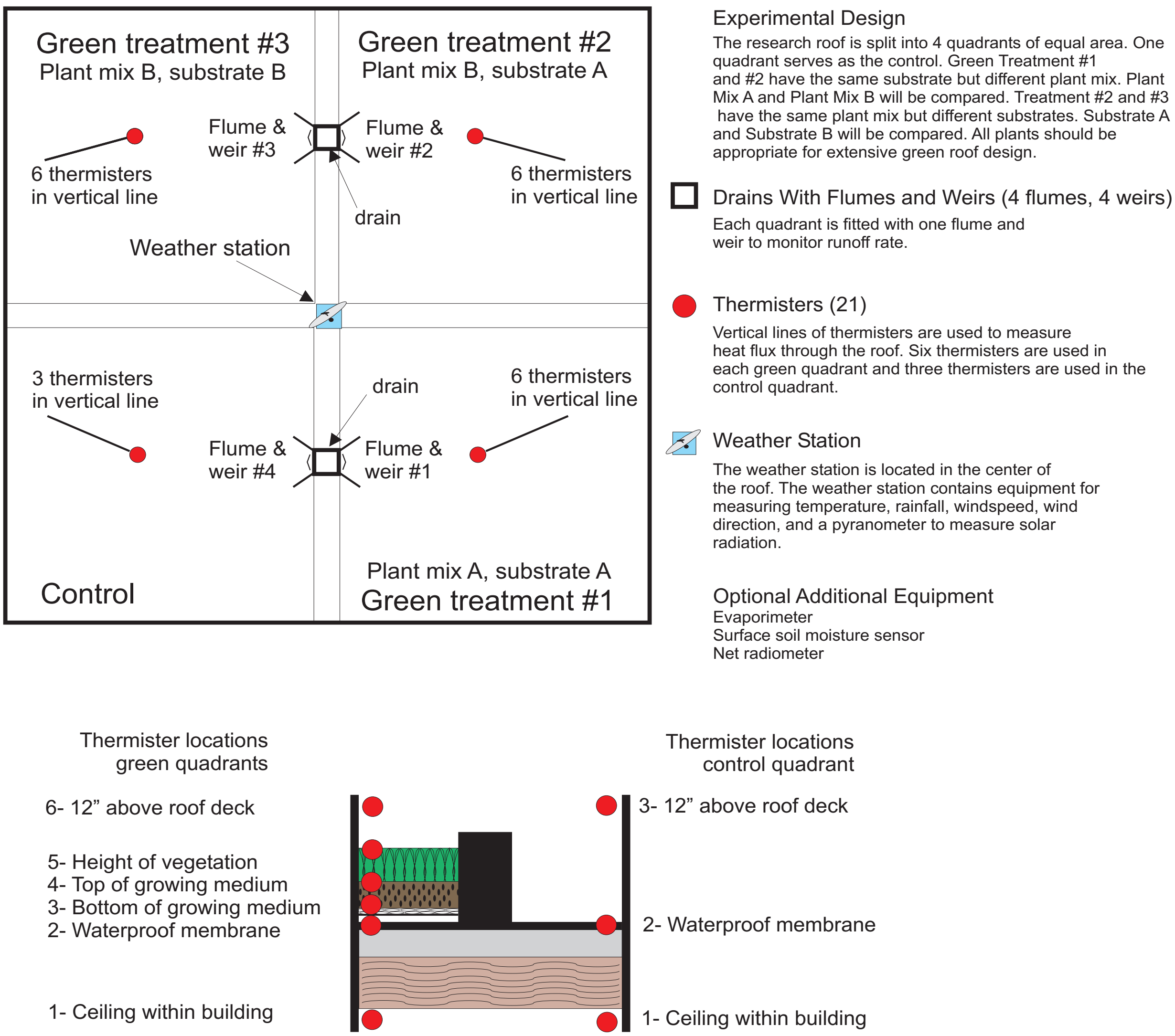

Figure 1. Green Roof Research Station experimental design.

with a weather station and each plot would be instrumented with monitoring equipment relevant to the energy and hydrology research sectors. This includes equipment for monitoring heat flux through the roof, as well as water retention and detention capacity (Table 2). The heat flux data, as well as data from a rooftop weather station, would be used in the energy-balance model to compare greened and non-greened vertical roof profiles and to correlate the results with heating and cooling requirements. Runoff rates, evaporation data, and precipitation data would be used in the hydrological model. Results from both energy and hydrology simulations would be used as inputs into the cost-benefit model. Measurements would be taken at regular time intervals – likely every 5 minutes – and would be recorded by an on-site data logger and then transferred remotely to an off-site computer.

Monitoring Protocols

Using the research station as a laboratory, we will design and test monitoring protocols that can be easily and inexpensively replicated at other green roof sites, even if the sites are dissimilar. We will then offer a monitoring package to

Table 2. Equipment list and costs based on a 4-plot experimental design, with 3 plots greened and 1 plot control. This list is included for illustrative purposes; actual equipment chosen and costs depend on roof conditions, green roof design, and project budget.

Measurement	Equipment	Cost per item	Total
Weather station			
Outdoor temperature	Thermocouple reference	1 @ $48.50 each	$48.50
Rainfall	Heated rain gauge	1 @ $1,045.50 each	$1,045.50
Wind speed/direction	Anemometer	1 @ $195.00 each	$195.00
Solar Radiation	Pyranometer	1 @ $275.00 each	$275.00
Energy balance			
Roof temperature profile	Roll of thermocouple wire	21 @ $790.00 total	$790.00
Heat flux	Soil heat flux plate	4 @ $315.00 each	$1,260.00
Soil water content	Water content reflectometer	3 @ $175.00 each	$525.00
Surface temperature	Infrared thermocouple	1 @ $745.00 each	$745.00
Stormwater runoff	Flume & weir	4 @ $750 each	$3,000.00
(Alternative)	(Pressure transducer)	(4 @$900 each)	($3,600.00)
Health – indoor air temp	Thermister	4 @ $80 each	$320.00
Compile data	Datalogger	1 @ $1,154.30	$1,154.30
	Datalogger support software	1 @ $85.00	$85.00
	Multiplexer	1 @ $868.15	$868.15
Download and interpret data	Laptop computer	1 @ $1,500	$1,500.00
	Modem, software		$733.95
Connection equipment	Mounts, cables, power		$1,333.35
On-site installation			$7,000.00
Freight			$162.00
Miscellaneous expenses			$3,959.30
		Equipment total	**$25,000-25,600**

* Funds for research personnel are not included.

others developing green roof projects in the New York metropolitan region. This will allow the developer to monitor green roof performance and will allow us access to a larger data pool from a wider spatial area. The additional data will be used to refine the models, compare the performance of different types of green roofs installed on different types of buildings, and study the effect of green roofs on the urban heat island effect and combined sewage overflows at scales beyond that of an individual building. The success of such monitoring will depend on close collaboration between green-roof adopters and the research group from an early stage in the design process.

Further Research

As initial research questions regarding energy and hydrology become resolved, the Green Roof Research Station will continue to provide a laboratory for researching new questions in the coming years. These could involve not only further aspects of green roofs, such as their effects on biodiversity (e.g., How do green roofs affect local populations of insects and birds? How do green roofs affect neighborhood and regional air quality?), but other aspects of ecological infrastructure as well. For example, How might vegetated walls and awnings affect New Yorkers and the buildings they live in? The green roof Research Station will be a resource for a broad group of scientists in the New York metropolitan region and beyond.

A Framework for Cost-Benefit Analysis of Green Roofs: Initial Estimates

Kenneth Acks, Cost-Benefit Group, LLC

Background

Environmental cost-benefit analysis is a decision support tool that provides a format for enumerating the range of benefits and costs surrounding a decision. In this study, cost-benefit analysis is used to determine the economic value of green roofs for both private decision makers (i.e., building owners) and public decision-makers (i.e., city and state policy makers) in New York City.

Environmental cost-benefit analysis involves determining which benefits and costs to consider, the means to measure them, and approaches for aggregating them, accounting for present and future cash flows associated with an investment related to the environment (such as a green roof). Many seemingly worthwhile environmental projects are never implemented. Such cost-benefit analysis can be used to choose among a range of alternatives, to compare seemingly different environmental projects, and to identify instances where specific groups are given advantages or disadvantages. Benefits and costs are converted into present values by discounting and summing future benefits and costs into present terms. These dollar-denominated present values allow decision-makers to compare the value of investments across potential uses of scarce financial resources.

Green roofs provide private and public property owners numerous potential benefits, but these benefits can be difficult to quantify and value. Benefits can take many forms including reductions in harmful environmental impacts and private cost savings associated with energy production. Green roofs may even provide aesthetic benefits and habitat ecosystem values. Quantifying the benefits from reducing environmental impacts can be difficult given the wide range of contexts in which green roofs might be developed. For example, a green roof installed on a Manhattan skyscraper will not have the same impact on energy use as one installed on a warehouse in Queens. Similarly, due to differences in the sewer and treatment system, green roofs installed in the Newtown Creek sewage-shed may not yield the same reduction in combined sewer overflow (CSO) as a similar sized system in the North River sewage-shed (see Tillinger et al., this report).

Moreover, even where environmental impacts can be reasonably quantified, it may still be difficult to derive the full economic value of the benefits. For example, sewer system complexities can compromise efforts to directly correlate reduced runoff volume (from green roofs) with reduced treatment costs. In addition, green roofs will have different levels of public benefits depending on the scale over which they are installed. We are therefore designing flexible computer models that will permit users to evaluate green roofs in a variety of ways.

Examples of cost-benefit analyses applied to green roof infrastructure in North America are rare. One example, a life-cycle cost (LCC) analysis of an individual building in Multnomah County, Oregon, shows that the project is a good investment for the county (Lee, 2004). This project however was partially paid for by outside funders and without this funding, the project would not have had a positive life-cycle cost (Lee, 2004). The LCC analysis included first cost (i.e., installation cost), replacement cost for the roof membrane, energy costs, stormwater costs, and the residual value of the roof at the end of the life-cycle period analyzed, with all cash flows converted to present value using a real discount rate of 3% per year (Lee, 2004). Energy impact was measured as the net effect on heating and cooling costs, and stormwater costs were based on a reduction in the City of Portland's stormwater fee. Although New York City has a building-level stormwater fee, green roofs have not yet been approved as stormwater infrastructure, so stormwater is not included in our building-level analysis for New York.

Another example is a 1999 study of buildings in Chicago, IL, conducted as part of the City's Urban Heat Island Initiative. The analysis estimates that greening all of the city's rooftops (30% of 224 square miles) would save $100 million in annual energy costs and would cut peak electricity demand by 720 megawatts (Roy F. Weston, Inc. 2000). This study projected cooling cost savings for a green roof on Chicago's City Hall to be about $3,600 annually (Roy F. Weston, Inc., 2000).

In addition, a cost-benefit analysis for a hypothetical medium-rise building in Singapore shows a positive life-cycle cost only when an extensive, inaccessible green roof is installed, and energy savings from year-round cooling requirements are included (Wong et al., 2003). The Singapore analysis includes assumptions on service life (i.e., the life of the waterproof membrane on a standard roof compared to that on a green roof), installation, operating and maintenance costs, and inflation and discount rates (Wong et al., 2003).

The present cost-benefit model considers the benefits and costs of individual green roofs as well as green roof infrastructure, with assumptions specific to New York City. It assumes uniform extensive green roofs planted with *sedums* and/or other related plants. The objective is to illustrate the methods employed in cost-benefit analysis and to provide preliminary estimates of benefit-cost ratios associated with green roofs. It is important to note that actual benefits and costs vary widely depending on building type and use, green roof location, green roof system selected, and the extent to which green roof infrastructure has already been adopted and/or supported at the municipal level.

Methods

Development of the green roof cost-benefit model involved the delineation and valuation of the potential benefits and costs of green roofs. Costs and benefits were aggregated and discounted in a spreadsheet model. Benefit-cost ratios for private (single building) and fifty percent green roof infrastructure scenarios are presented.

Determining Benefits and Costs

Potential benefits and costs of green roofs were determined based on a survey of prior research. Benefits and costs were then divided into private and public. Private costs are those paid for by a building owner or residents, for example green roof installation and maintenance costs. Private benefits include energy savings and cost-savings associated with the longer service life of a roof membrane. Public costs might include a subsidy or other government program paid for by taxpayers that is aimed at increasing adoption of green roof infrastructure. Public benefits are those experienced by a preponderance of city residents, regardless of whether the building they live in has a green roof, and include reduced stormwater runoff and urban heat island reduction.

Private and public benefits were further divided into two tiers. Tier I includes benefits and costs covered by the research areas covered in this report related to energy, hydrology, and the urban heat island and are listed in Table 1. In general, Tier I costs and benefits appear to be more significant and well-defined in the near-term. Tier II adds potential benefits such as improved air quality and public health, reduced greenhouse gas emissions, increased property values due to sound insulation, and the aesthetic enjoyment derived from viewing and being near plants.

Cost-benefit Model Calculations

A cost-benefit model for green roofs was developed in Excel permitting the user to enter

Table 1. Baseline data for cost-benefit analysis.

Fixed inputs	Value
Private green roof scenario	
Roof area for an average flat roof in New York City (sq. ft.)	2,397
Percent of roof area greened	75%
Green roof area (square feet)	1798
Time period (number of years)	55
Private discount rate	8.00%
Inflation rate	3.00%
50% Green roof infrastructure scenario	
Flat roof area in New York City (acres)	21,249
Percent of New York City's flat roofs greened	50%
Percent of each roof greened	75%
Flat roof area greened (acres)	7968
Approximate number of roofs greened	144,832
Average size of each green roof (square feet)	2,397
Percent of land area in New York City with green roofs	4.2%
Time period (number of years)	55
Social discount rate	5.00%
Inflation rate	3.00%

numerous assumptions that in turn generate differing financial output. The model can explore several cost and benefit scenarios and scales of implementation. Two general model scenarios were chosen: 1) a private green roof scenario and 2) a 50% green roof infrastructure scenario. Flat roof area data from Hydroqual/Comcarto were used to generate roof areas associated with each scenario (Hydroqual/Comcarto, 2003). The private scenario assumes a single green roof of 1,798 square feet (167 square meters). The infrastructure scenario assumes 7,968 acres (32 km^2) of green roofs. This corresponds to about 144,832 roofs or 4% of New York City's total land surface area of 189,131 acres (765 km^2).

In the private analysis, we assume that the green roof is paid for by the building owner and benefits the owner and/or building residents. In the infrastructure analysis, the costs associated with administering a municipal-level support program for green roofs are added to installation costs, and public benefits such as stormwater runoff and heat island reduction are included.

Model inputs include baseline data for each scenario and variable assumptions reflecting high, medium, and low green roof performance. The medium performance scenario represents our current best guess for all parameters. The low and high scenarios are used to illustrate the range of benefits and costs associated with extensive green roofs. However, because all the high-performance parameters (i.e., high stormwater retention, large heat island reduction, low costs, etc.) are grouped into a single scenario, this scenario is likely unrealistically high. Conversely, the low performance scenario results are aggregated in the other direction. All data were converted into common units in the model and the time period for the analysis is 55 years.

Tier I Private Benefits and Costs

Installation costs The installation costs represent the private investment in a green roof project. The estimated cost of installing a standard (non-green) roof is $9 per square foot (W.P. Hickman Systems, Inc., 2003; verified with Marshall and Swift Manual, 1998). Industry estimates from green roof manufacturers range from about $10 per square foot to $25 per square foot or more for an extensive green roof. In general, the cost of installing an extensive green roof (including new waterproof membrane, drainage layer, growing medium, and vegetation) is about twice as expensive as installing a new waterproof membrane on a standard roof. Therefore a cost of $18 per square foot was used for the green roof installation cost in the medium scenario. In the high-performance scenario, the cost was reduced to $12 per square foot and in the low scenario it was increased to $24 per square foot.

Architecture and engineering costs Architecture and engineering costs associated with green roof installation was assumed to be 0.20% of installation costs.

Service life On a standard roof, the waterproof membrane is generally replaced every 20 years due to damage from ultraviolet radiation. Because the green roof protects the membrane from sunlight damage and large-amplitude diurnal temperature cycles, its service life is expected to double. Following Wong et al. (2003) and Lee (2004), this analysis assumes a standard roof service life of 20 years and a green roof service life of 40 years. In other words, although a green roof is approximately twice as expensive to install, its service life is doubled. The low scenario assumes that there was no improvement in service life and the high scenario assumes a 60-year service life.

Maintenance costs For standard roofs, maintenance costs of $0.10 per square foot were estimated based on data from the Institute for Real Estate Management (IREM) (IREM, 2003). On extensive green roofs, minimal maintenance is needed; estimates range from $0.06 to $1.25 per square foot per year (Giesel, 2003; Peck and Kuhn, 2003). In this analysis, a median value of $0.60 per square foot per year is used for the medium-performance scenario. The high-performance scenario assumes that the maintenance costs for a green roof will be no higher than the maintenance costs for a standard roof, and the low-performance scenario assumes the costs will be $1.10 per square foot per year.

Energy used for cooling Green roof impact on energy used for cooling is the most difficult input parameter to estimate because it will not be the same for any two buildings. Cooling demand depends on building specifications, location, and use, among other factors. An average cost of cooling a building with a standard roof in New York City was estimated at $0.16 per square foot through five independent calculations. Sources for the calculations include the Energy Information Administration in the U.S. Department of Energy (EIA, 2004), the New York State Energy Research and Development Authority (NYSERDA, 2004), the Building Owner and Manager's Association 2003 Experience and Exchange Report (BOMA, 2003), Efficient Windows (EW, 2004), and the EPA Energy Star Roofing Comparison Calculator (EPA, 2004). The medium scenario assumed that a green roof could reduce energy demand for cooling by 15%. This is higher than preliminary results from an experiment at the Pennsylvania State University Center for Green Roofs Research, which show a reduction of approximately 10% (Berghage, 2004). However, it is substantially lower than the 75% reduction in cooling demand during the summer months found for a small experimental building in Ottawa (Liu and Baskaran, 2003). In a Manhattan skyscraper, the reduction may be less than 1% and for a single-story office building in Queens, the reduction could be more than 20%.

Tier I Public Benefits and Costs

Green roof infrastructure would result in the following additional public benefits and costs.

Urban heat island The urban heat island effect refers to an increase in urban temperatures as compared to surrounding suburban and rural temperatures (see Solecki et al. in this report). Green roof infrastructure could reduce outside urban air temperatures, and this could result in lower demand for cooling throughout New York City in the summer. Results from the research in this report show that 50% green roof infrastructure could reduce surface temperatures by 0.1 to 1.4°F. We assume a linear relationship between surface temperature and air temperature and use the average value of 0.8°F for the medium-performance scenario. 0.1°F is used in the low-performance scenario and 1.5°F is used in the high-performance scenario. We assume that air conditioning is turned on when the temperature rises above 65°F; this is used in heating-degree-day calculations. We estimate average summertime temperatures in New York City at 80°F based upon temperatures registered in recent years. The percentage reduction in this 15°F gap with green roofs was calculated. With a 0.8°F reduction, the gap was reduced by 5% (from 15°F to 14.2°F), resulting in a 5% reduction in energy demand for cooling with a total cost savings of $213 million. In the low-performance scenario, demand was reduced by 0.7% and in the high-performance scenario demand was reduced by 10%.

Stormwater runoff capital expenditures and operating costs The ability of green roof infrastructure to capture rainfall during storms could reduce the amount of stormwater that enters the sewer system and is then directed to wastewater treatment plants. This could have the effect of reducing capital expenditures and operating costs for wastewater treatment. In this analysis, we assume a linear relationship between the amount of water that enters a treatment plant and the capital expenditures. Current annual capital costs are ~$180 million based on data published in the New York City Budget and Mayor's Management Report (NYC IBO, 2003), and the Independent Budget Office of the City Council (2004). In the medium scenario, we assume that green roofs can retain 50% of the rainwater that falls on them (see Tillinger et al. in this report). This high scenario assumes 80% capture, and the low scenario assumes 20% capture. Rainfall capture is multiplied by land-area greened (4% of New York City's land area with a 50% green roof infrastructure scenario) and percent combined sewage from rainwater (an estimated 65% for New York City) to obtain the percent reduction in combined sewage that enters the sewer system. This figure is then multiplied by a scale factor of 90% because it is unlikely that a 10% fall in CSO will reduce expenditures by 10%. With the medium scenario, capital expenditures were reduced by 1.9%. With the low scenario they were reduced by 0.6% and with the high scenario by 3.4%. We further assume that green roofs would cut operating costs by 10% of capital expenditures or $18 million.

Scale factor for installation and maintenance costs In the private scenario, installation costs for a green roof were estimated at $18 per square foot. The infrastructure scenario involves greening over 144,000 rooftops. If adopted, economies of scale would almost certainly bring down the costs. One study suggests that for each doubling in production volume of several selected environmental technologies, the amount by which costs decline is in the range of 0.7 to 0.9 (Papathanasiou and Anderson, 2001; see also IEA, 2000). Scaling up from a single green roof to over 144,000 green roofs involves approximately 18 doublings, which would reduce costs to 0.02 * $18 per square foot or $3.6 square foot. However, given the base cost of $9 per square foot for a standard roof, a reduction of this magnitude is unlikely. Instead, we assume that scaling would reduce installation costs to $15 per square foot for the medium scenario. In the high-performance scenario, cost is reduced to $10 per square foot, just above the cost of a standard roof. The low-performance scenario assumes that cost remains at $18 per square foot.

Program costs A green roof infrastructure program would likely require some degree of administrative support at the municipal level. Initial program administration and setup costs are estimated at 0.1% - 0.3% of investment (installation) costs or just over $30 million for the medium scenario.

Tier II Private Benefits

Sound reduction According to research done by Zinco, a green roof company in Germany, green roofs provide sound insulation of approximately 3 decibels (Zinco, 2003). This figure is used to estimate the change in property value for buildings with green roofs in New York City.

Food production Several green roofs have been used to grow food crops, including the Fairmont Hotel in Vancouver. Food production value is estimated at $0.10 per square foot for the medium scenario based on the Fairmont Hotel's production (GRHCa, 2003).

Private aesthetic benefits Aesthetic benefits are based on the value of enjoying a green roof as a building amenity. For the medium-performance scenario, it was assumed that the green roof would benefit 6 people: two of whom would be willing to pay $50, two $25, and two $10. For the high-performance scenario, this figure was doubled and for the low scenario, it was cut in half.

Tier II Public Benefits

Greenhouse gases A study in Toronto estimated that greening all rooftops could cut greenhouse gas emissions by 2.4 megatons annually (GRHCb, 2003). To obtain a crude estimate of the potential impact in New York, we multiplied this figure by the population of New York relative to the population of Toronto. Savings for the medium-performance scenario were $0.18 per square foot (see Parry, 2003; Tol, 2003; CEA, 1998).

Air pollution The same study indicates that 10.8 square feet (1 meter) of grass roof can remove 0.44 pounds of airborne particles per year (GRHCb). Thus, airborne particulates should be reduced by 0.04 pounds per square foot of green roof. The U.S. Forest Service estimates a benefit of $2.2 per pound or $1.43 per square foot (Nowak et al., 2002). Reductions in nitrogen oxides, ozone, sulfur dioxide, and carbon monoxide were assumed to be 10% – 30% of the reduction in airborne particulates. The average value of 20% was used in the medium-performance scenario. Dollar values associated with the reductions varied by pollutant and were estimated based on the Forest Service model.

Health Health savings were estimated based on mean willingness to pay for a longer and/or healthier life based on EPA numbers.

Public aesthetic benefits The private analysis assumed the green roof would have aesthetic value for a small number of building residents. In the public analysis, we assume in the medium scenario that each of the 144,000+ green roofs will be enjoyed by approximately 12 people so that about 1.7 million of the city's residents would benefit from 50% green roof infrastructure. In the low-performance scenario, this number is cut in half; in the high-performance scenario, this number is doubled.

Model Output

The model generates a benefit-cost ratio for each scenario. The benefit-cost ratio is defined as the aggregate discounted benefits over a specified time period divided by the aggregate discounted costs over the same time period.

Benefits, costs, and economic parameters such as discount and inflation rates were input into the model. Present-value calculations were used to convert expected future monetary flows into a single present value based on the premise that a dollar today is worth more than a dollar tomorrow due to risk and uncertainty. A higher discount rate reduces the present value of future cash flows. Future cash flows are converted into present value using the formula:

$$\text{Present Value} = \frac{\text{Future Value}}{(1+r)^t}$$

Where r = discount rate; and
t = time period (in this case measured as years from the present)

Industry surveys can help to estimate appropriate discount rates. With respect to real estate values, surveys by Korpacz and the Real Estate Research Corporation are used (PricewaterhouseCoopers, 2003). Discount rates for an office building range from 8.5% for a prime Class A building in Midtown Manhattan to 12.0% for an old Class B building in a less desirable location (PricewaterhouseCoopers, 2003). Rates for hotels and nursing homes with uncertain income streams rise to between 13% and 25% (PricewaterhouseCoopers, 2003). Real discount rates (i.e., discount rates adjusted to reflect purchasing power) typically applied to environmental issues range from 2% to 6%. Based upon a survey of 2,160 economists in 48 countries, Weitzman concluded that the discount rate for expected benefits and costs of projects proposed to mitigate the possible effects of global climate change should be 4% for the immediate future (years 1-5), 3% for years 6 to 25, 2% for years 26 to 75, 1% for years 76 to 300, and 0% for benefits and costs occurring more than 300 years hence. A survey of 50 economists produced similar means and standard deviations. For a single estimate, Weitzman suggests the use of 2% (Weitzman, 2001). A California study more analogous to this analysis entitled "The Costs and Financial Benefits of Green Buildings" used a discount rate of 5% (Kats et al., 2003).

In this analysis, a private discount rate of 8% and a social discount rate of 5% are used. In addition, the model currently assumes that technological change and economies of scale will reduce the cost differential over time. However, potential technical changes must be studied more thoroughly.

Finally, the model assumes that expenditures related to green roofs may be multiplied throughout the economy creating additional income and jobs. At present, the model uses a simple multiplier for income generation and job creation. Successful projects also generate tax revenues for governments. By multiplying income generated and expected property value increase by tax rates, the present value of fiscal impacts are estimated.

Results

The results show a positive benefit-cost ratio for the medium (best-guess) performance scenario only when Tier II benefits are included (See Tables 2 – 4). This indicates that although individual green roofs may not be cost-effective,

Table 2. Benefit-cost ratios for all scenarios.

Tier I & Tier II results	Performance scenario		
Tier I	**Low**	**Medium**	**High**
Benefit-Cost Ratio Tier I, Private	0.34	0.46	1.31
Benefit-Cost Ratio Tier I, Public	0.53	0.65	1.57
Tier II	**Low**	**Medium**	**High**
Benefit-Cost Ratio Tier I & II, Private	0.38	0.54	1.85
Benefit-Cost Ratio Tier I & II, Public	0.66	1.02	3.87

Table 3. Preliminary cost-benefit analysis results for Tier I and Tier II private scenario.

Average New York City Building Tier I & Tier II	**Low**	**Medium**	**High**
Private benefits – Tier I			
Service life			
Standard roof installation costs foregone	$28,369	28,369	28,369
Standard roof maintenance costs foregone	3,822	3,822	3,822
Cooling	1,271	2,848	7,459
Total private benefits – Tier I	33,462	35,039	39,650
Private costs – Tier I			
Installation cost of green roofs	(57,705)	(54,821)	(26,629)
Architecture and engineering	(115)	(110)	(53)
Maintenance costs of green roofs	(39,223)	(21,394)	(3,566)
Total private costs – Tier I	(97,043)	(76,325)	(30,247)
Net private benefits – Tier I	(63,581)	(41,286)	9,403
Benefit/Cost Ratio Tier I Private	**0.34**	**0.46**	**1.31**
Initial expenditures green roofs	(57,518)	(43,138)	(28,759)
Initial expenditures on standard roofs foregone	(21,569)	(21,569)	(21,569)
Difference in initial cxpenditure	(35,949)	(21,569)	(7,190)
Income generated	42,202	46,217	56,126
Jobs (construction)	0	0	0
Jobs (permanent)	(1)	(1)	0
Fiscal impacts (change in tax revenues)	(4,891)	(2,339)	3,420
Private benefits – Tier II			
Agricultural	8	80	120
Aesthetics/recreation	787	3,149	12,597
Sound	2,225	3,067	3,741
Total private benefits Tier II	3,020	6,296	16,458
Total private benefits – Tier I & Tier II	36,482	41,335	56,108
Net benefits – Tier I & Tier II	(60,561)	(34,990)	25,861
Benefit/Cost Ratio Tier I & Tier II Private	**0.38**	**0.54**	**1.85**

green roof infrastructure is cost-effective when the full range of benefits is considered. Furthermore, the high-performance scenarios, which may become feasible as green roof technology is improved and the market for green roof infrastructure expands, show a positive benefit-cost ratio at both the private and public level. The results are particularly sensitive to the green roof installation cost. Here we assume that an individual green roof costs twice as much as an individual standard roof; however, as more green roofs are built, the costs are likely to be reduced. Therefore, in the public analysis, we assume that the cost is reduced somewhat to $15 per square foot. This reduction alone is not enough for a positive benefit-cost ratio within Tier I, but when additional benefits are added and a wider population is assumed to obtain the aesthetic benefits of green roofs, the benefit cost ratio becomes positive.

Table 4. Preliminary cost-benefit analysis results for Tier I and Tier II public scenario.

50% Green Roof Infrastructure	Low	Medium	High	Annualized Medium
Private benefits – Tier I				
Service life		(lowers relative costs below)		
Standard roof installation costs foregone	$4,108,700,000	4,108,700,000	4,108,700,000	333,535,896
Standard roof maintenance costs foregone	553,600,000	553,600,000	553,600,000	44,940,120
Cooling	184,100,000	412,500,000	1,080,300,000	33,485,910
Total private benefits – Tier I	4,846,400,000	5,074,800,000	5,742,600,000	411,961,926
Social/public benefits – Tier I				
Water runoff capital expenditures	21,800,000	54,400,000	87,100,000	4,416,081
Water runoff operating cxpenditures	2,200,000	5,400,000	8,700,000	438,361
Energy/heat island cooling	21,600,000	212,600,000	622,800,000	17,258,435
Greenhouse gases (carbon dioxide)	1,900,000	7,800,000	31,200,000	633,188
Total social/public benefits – Tier I	47,500,000	280,200,000	749,800,000	22,746,065
Total private & social/public benefits – Tier I	4,893,900,000	5,355,000,000	6,492,400,000	434,707,991
Private costs – Tier I				
Installation cost of green roofs	(6,268,100,000)	(6,616,500,000)	(3,856,700,000)	(537,113,991)
Architecture amd engineering	(12,500,000)	(13,200,000)	(7,700,000)	(1,071,549)
Maintenance costs of green roofs	(2,840,400,000)	(1,549,300,000)	(258,200,000)	(125,769,018)
Total private costs – Tier I	(9,121,000,000)	(8,179,000,000)	(4,122,600,000)	(663,954,558)
Social/public costs – Tier I				
Program administration and setup	(17,400,000)	(9,600,000)	(3,900,000)	(779,308)
Program maintenance	(34,100,000)	(20,000,000)	(10,400,000)	(1,623,559)
Total social/public costs – Tier I	(51,500,000)	(29,600,000)	(14,300,000)	(2,402,868)
Total private & social/public costs – Tier I	(9,172,500,000)	(8,208,600,000)	(4,136,900,000)	(666,357,426)
Net benefits total – Tier I	(4,278,600,000)	(4,278,600,000)	(2,853,600,000)	2,355,500,000
Benefit/Cost Ratio Social/Public – Tier I	**0.53**	**0.65**	**0.53**	**0.65**
Initial expenditures green roofs	(6,247,800,000)	(5,206,500,000)	(4,165,200,000)	(422,653,064)
Initial expenditures on standard roofs foregone	(3,123,900,000)	(3,123,900,000)	(3,123,900,000)	(253,591,838)
Difference in initial expenditure	(3,123,900,000)	(2,082,600,000)	(1,041,300,000)	(169,061,225)
Income generated	6,117,375,000	6,693,750,000	8,115,500,000	543,384,989
Jobs (construction)	33,222	33,437	(3,360)	2,714
Jobs (permanent)	(65,825)	(38,048)	27,712	(3,089)
Fiscal impacts (change in tax revenues)	(213,751,875)	(51,078,750)	519,592,500	(4,146,469)
Private benefits – Tier II				
Agricultural	1,200,000	11,600,000	17,400,000	941,664
Aesthetics/recreation	228,100,000	912,200,000	3,648,900,000	74,050,538
Sound	322,200,000	444,200,000	541,800,000	36,059,251
Total private benefits – Tier II	551,500,000	1,368,000,000	4,208,100,000	111,051,453
Total private benefits – Tier I & Tier II	5,397,900,000	6,442,800,000	9,950,700,000	523,013,379

Table continued on next page.

50% Green Roof Infrastructure	Low	Medium	High	Annualized Medium
Public benefits – Tier II				
Particulates removed	80,500,000	321,800,000	965,400,000	26,123,068
NOX removed	12,200,000	97,400,000	289,600,000	7,906,734
Ozone removed	12,200,000	97,400,000	438,500,000	7,906,734
SO2 removed	2,900,000	23,100,000	104,100,000	1,875,211
Carbon monoxide removed	1,800,000	14,400,000	64,800,000	1,168,963
Total social/public Benefits -- Tier II	109,600,000	554,100,000	1,862,400,000	44,980,709
Total social/public benefits – Tier I & Tier II	157,100,000	834,300,000	2,612,200,000	67,726,774
Total private and public benefits – Tier II	661,100,000	1,922,100,000	6,070,500,000	156,032,162
Total private and social/public benefits – Tier 1 & Tier II	6,059,000,000	8,364,900,000	16,021,200,000	679,045,542
Net benefits total – Tier I & Tier II	(3,113,500,000)	156,300,000	11,884,300,000	12,688,116
Benefit/Cost Ratio Social/Public – Tier I & Tier II	**0.66**	**1.02**	**3.87**	**1.02**

In general, it is important to include both the benefits that are more easily quantifiable and those that are not, in environmental cost-benefit analysis. The exclusion of benefits that are not easily measured may return a negative benefit-cost ratio for environmental projects that are actually cost-effective.

Caveats

These results should be considered as preliminary estimates. To the extent possible, model assumptions were based on empirical studies. The number of studies is limited at the present time forcing us to utilize data with limited applicability to conditions in New York City. Given these limitations, no building specifications beyond square footage were used in the model.

Conclusion

Green roof infrastructure could be a cost-effective way to help solve some of New York City's environmental and human health problems, when multiple private and public benefits are considered together.

Further Research

The cost-benefit analysis could be improved with additional empirical research on each of the potential benefits and economic impacts of green roofs in New York City. Additional research into capital and operating expenditures for stormwater through examination of publications and interviews of knowledgeable individuals is a priority. Customizing the estimates for the New York City Region by conducting surveys to measure potential aesthetic and recreational benefits is also important.

The flexibility of the spreadsheet permits us to look at several different valid paths to obtaining estimates of costs and benefits. Further disaggregation of calculations would allow greater customization for the New York City Region. Tie-in to other models including the EPA DOE2 model to measure energy used by buildings, the NY Externalities Model, and Input/Output models such as REMI and IMPLAN could also improve the analysis.

Sensitivity tests, further scenario analysis, and a consideration of a variety of spatial scales such as: 1) square foot, 2) building, 3) Census tract, 4) zip code, 5) regulator basin, 6) sewage-shed, 7) city, 8) state, and/or 9) region could help provide insights on the necessary scale of adoption for certain benefits to be realized.

Comparison of costs and benefits of green roof infrastructure, and other strategies, approaches and technologies such as reflective roofing and stormwater retention Best

Management Practices (BMPs) could help policy makers determine whether green roof infrastructure is a good choice for New York City.

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Epilogue

Urban Ecological Infrastructure

Joel Towers and Karla Rothstein

If this research report from New York green roof researchers were a typical scientific report, it might be strange to find an epilogue as the concluding statement. Similarly, if this were a typical policy paper it would be odd to end with this particular form of writing. Epilogues are most commonly written as the concluding section of a literary work or performed by an actor at the end of a play (O.E.D, 1993). But the work of this group is not typical. The members cannot easily be defined as exclusively scientific or public policy-oriented. Rather, it is a transdisciplinary assemblage of natural and social scientists, design professionals and economists. The creative tension that emerged through our collaborative effort to explore green roofs as a component of a larger urban ecological infrastructure has resulted in a report that is part science, part policy, and in the end something entirely different than any subset of us would have produced independently. The science leads to tantalizing questions that need to be addressed through further funded basic and applied research. The policy issues of green roofs are compelling and need to enter the public debate on the future of the city and its ecological resilience. The economic analysis must be expanded in scope and duration and tested even as the conditions that constitute its foundation are altered by shifts in social capital. But what bridges, and to some degree holds this report together, is a narrative structure that permeated our many meetings and winds through this first publication. This is a story of cities as complex ecological organisms whose socio-natural systems are measured in degrees of resilience. And so we end with an epilogue that frames the report in a larger context and attempts to chart a path forward.

In the preface to this report, Rosenzweig introduces the transdisciplinary founding principle as the integration of "scientific knowledge and methods with practical mechanisms for achieving urban sustainability." Defining this scope as the "interactions of the physical, biophysical, and social realms," they immediately set the challenge of scalar integration across disciplinary perspectives as an overarching concern (Rosenzweig, this report). Interestingly however, with the exception of the report title, nowhere in their preface does the specific site or vehicle for investigation – the green roof – appear. Far from revealing ambivalence about the role of the green roof in urban ecological infrastructure, this omission signals a desire to return to the broader scientific and social complexities that research needs to address. And yet the question remains. While green roofs have offered a way into the question of the 21st Century sustainable city, they are but one path, so why did we begin with the roof? One answer is that large-scale, networked, and emergent questions of ecology and landscape permeate the report. From this particular scalar perspective the more than 1.3 billion square feet of roof surface in New York City, the vast majority of which, 925 million square feet, is flat-roofed (Hydroqual/Community Cartography, 2004), is an obvious point of departure. And yet, while it is clear that individual green roofs serve a range of discrete ecological and social functions, the problem of scale immediately returns. It is not possible to simply aggregate these distinct roofscapes and suggest that they necessarily mean more than the sum of their parts. To begin with, buildings are volumetric enclosures, not two-dimensional, extruded flat surfaces. Correcting for volumetric complexity is difficult in the current work, as diversity in building materials and forms inserts untenable indeterminacy into the equations. Green roofs as social spaces are equally difficult to qualify as they exist at the intersection of environment, design and the never-settled relationship between private and public social space. Financing, regulation and building codes further complicate the calculus and it is, therefore, not surprising that strategic, wide-scale development of green roofs has met with varying degrees of success. Nonetheless, farsighted municipalities have advanced the idea that green roofs can be understood as part of an emerging field of ecological design and construction, which, when explored at an urban scale leads to a series of questions: Can such a thing as an "urban ecological infrastructure" exist beyond traditional understandings of urban forestry, park systems, waterways, etc.? If so, how would it acquire social meaning and social capital? Could urban vegetative roof structures be seen as harbingers of an emerging socio-natural urban ecology, through which cities assign value to human interactions with the natural world on an infrastructural scale? This is certainly one way to read Frith and Gedge's assertion that "[t]he most important catalyst of green roof construction in Britain in the past five years has been the drive to reconcile biodiversity conservation with urban renewal" (Frith and Gedge, 2004).

If green roofs are to be evaluated as a component of an ecological infrastructure, they must cover enough of the city to have a measurable impact on microclimate, energy, and material flows as well as the cultural imagination of what the city is and can become. This report explores precisely that. And while our conclusions call for more study, we are significantly closer to being able to recommend and predict the impact of this particular aspect of an ecological infrastructure deployed across an urban field. Given sufficient acreage, green roofs of varying sizes, functions, and designs would constitute a mosaic of inter-related vegetative spaces; individual ecological patches whose benefits could be greatly multiplied to the point of producing larger-scale transformations of urban ecologies. Operating in this complex infrastructural fashion, green roofs would attain a social relevance that would produce a feedback loop reinforcing their deployment across the urban landscape, and greatly impacting their perceived value.

From this perspective we can begin to ask how green roofs can be creatively considered in an urban context. Are they a sign of changing perceptions about the city? Do they indicate an extension of nature within the city or do they point to a commingling of the natural and built environments in a manner that might lead toward increased resilience and a more integrated socio-natural relationship? How do they impact the dynamics of the urban organism? What can they tell us about other ecological questions at the scale of urban infrastructure?

The scale and position from which these questions are explored will affect how green roofs are seen and understood. Urban green roofs as individual entities may be viewed as extensions of private space. They may also be seen as providing specific, localized benefits to the operation of buildings. Collectively, however, they have the capacity to impact urban ecology and, therefore, may also be understood in infrastructural terms. Mikami's study of Tokyo is instructive of this scalar shift, examining how the aggregation of green roofs in that city are seen as part of an emerging infrastructure that has the potential to mitigate the urban heat island effect (Mikami, 2004).

Surfacing through this report is confirmation that green roofs acquire social capital in different ways (often related to scale) that may or may not facilitate their widespread application in urban environments. Understanding this calculus is essential if green roofs are to be one tool in the larger project of shifting the post-industrial city towards ecological (natural and social) sustainability. This shift is in its formative stages and charts a possible alternative urban future desperately in need of exploration. There is much work to be done, and as the geographer David Harvey reminds us: "[T]he integration of the urbanization question into the environmental-ecological question is a sine qua non for the twenty-first century. But we have as yet only scraped the surface of how to achieve that integration across the diversity of geographical scales at which different kinds of ecological questions acquire the prominence they do" (Harvey, 1996). Which brings us back to Rosenzweig's preface.

Running through the questions of scale, position and impact are the pragmatic realities of implementation. As Acks (Acks et al., this report) writes "Many seemingly worthwhile environmental projects are never implemented." He establishes three potential roadblocks to the realization of those projects. The first is the calculus of costs versus benefits, the second is related to the indeterminacy of that calculus, and the last is an issue of perceived value. Through unique constellations of collaborative transdisciplinary research, researchers in this report have the potential to continue to substantively inform these variables, toward practical applications and assessments of potential socio-natural reconfigurations of the urban terrain. The group has been many things, but mostly it is a beginning. This report report is intended to present research and thinking to date on the green roofs chapter of our larger ecological and infrastructural ambitions.

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Note: Parts of this epilogue appear under the title "Imagining the City: Urban Ecological Infrastructure" by Joel Towers in *Green Roofs: Ecological Design and Construction*. Atglen, PA: Schiffer Publishing. 158 pages.

Appendix I

Rough Estimation of Energy and Water Relations for Variously Treated Rooftops in New York City—Hypothetical Calculations

Daniel Hillel

Energy Relations

We begin with the energy-balance equation (Hillel, 1998):

$$S = (Js + Ja)(1 - a) + (Jli - Jlo) - A - LE \qquad (1)$$

Where S is downward heat flux into the ground surface (i.e., into the building under a flat roof). Js is the incoming flux of shortwave radiation directly from the sun, Ja is the shortwave diffuse radiation from the atmosphere (sky), Jli is the incoming long-wave radiation flux from the sky, Jlo is the outgoing longwave radiation, a is the albedo, A is the sensible heat flux transmitted from the surface to the air, and LE is the evaporative heat flux, a product of the evaporative rate E and the latent heat per unit quantity of water evaporated, L.

Assume, for simplicity, that the diffuse short-wave and longwave sky radiations (Ja and Jli, respectively) are negligible. (They are often small in comparison to the other fluxes.). Hence

$$S = Js(1 - a) - Jlo - A - LE \qquad (2)$$

For a bare roof (no vegetation), we assume that there is no evaporative heat flux, since, for the most part, there is no standing water; thus, LE = 0.

We estimate S from the following considerations:

The flux of radiant energy received at the outer envelope of the atmosphere (known as the "solar constant" is about 1400 Watts per square meter perpendicular to the incoming radiation. The flux of solar radiation actually reaching any portion of the earth's surface varies according to latitude, season, cloudiness, and atmospheric turbidity.

Assume that the warm season (the period of air-conditioning in New York) lasts 140 days, of which 100 days are bright sunny days. If the flux of solar radiation on bright days averages about 50% of the solar constant during 10 hours (of the total day-length of 14 hours), then:

Js = 0.5(1400 Watts per hour)(10 hours) = 7000 Watt-hours per day = 7 Kilowatt-hours per square meter per day (7 KWH/day)(100 bright sunny days per year) = 700 KWH per square meter per year

Black Roof Estimation

We now do the calculation for a hypothetical black (smooth and flat) roof, for which the albedo a = 0.1, evapotranspiration LE = 0, Jl = 0.1 of Js, and sensible heating of the air A = 0.1:

S = [(1 – 0.1) – (0.1 + 0.1)]Js = (1 – 0.3)Js = (0.7)(700 KWH/yr) = 500 KWH per square meter per year

The total area of flat roofs in New York's five boroughs is 21,250 acres, equal to 85,000,000 square meters. Hence the total annual heat load into black-roofed buildings is:

S = (500)(85,000,000) = 42,500,000,000 KWH

Assume, for the sake of argument, that the above heat load must be dissipated by air-conditioning, that the air-conditioners are 50% energy-efficient, and that the cost of electricity is \$0.1 per KWH. Then the annual cost of air-conditioning for all black-roofed buildings in New York would be:

(\$0.1/0.5)(42.5 BKH) = \$8.5 billion dollars

White Roof Estimation

For comparison, let us assume that all the roofs of New York were painted white, so that the albedo (a) would be increased from 0.1 to 0.7. Because white surfaces would be cooler than black surfaces, Jlo (emitted long-wave radiation) and A (sensible heating of the air) would then both reduced to, say, 0.05. So, for white roofs,

$S = (1 – 0.7)Js – (0.05 + 0.05)Js = (1 – 0.8)Js$
$S = (0.2)(700) = 140$ KWH per square meter per year

This is less than one-third of the heat load affecting the buildings under the black roofs.

Again we multiply the last figure by the total area of roofs in New York City to obtain the total heat load under white roofs:

$S = (140)(85,000,000) = 11.7$ billion KWH per year

Assuming the same 50% efficiency for air-conditioners, we estimate the cost of cooling white-topped buildings to be

(\$0.1/0.5)(11.7 BKH) = \$2.34 billion dollars

Green Roof Estimation

Now assume that a shallow layer of "soil" (or of a porous, particulate material simulating soil) covers all the roofs, constituting a medium for the growth of a dense stand of active vegetation. To grow in a very shallow rooting zone and to survive repeated dry spells, the vegetation to be grown will necessarily be of the drought-tolerant "xerophytic" type.

The albedo value of vegetation may vary between 0.15 and 0.4. Xerophytes generally exhibit higher values of albedo. We therefore assume a mean value of 0.3.

Fully active vegetation, growing in a medium well-endowed with water, typically transpire at nearly all (say, 80%) of the meteorologically imposed potential evapo-transpiration rate. In our case, because of the expected occurrence of repeated dry spells between successive rainfall events, we may assume that the vegetation transpires, on average, at a rate roughly equal to 40% of potential evapotranspiration.

Figures can be obtained for the potential evapotranspiration prevailing in New York, and its variation over the seasons. In our case, we may use the starting assumption that the potential evapotranspiration is roughly equal to the flux of incoming short-wave solar radiation. Accordingly, the value of the term LE in the energy balance equation = 0.4Js.

Because of its cooling effect on the surface, the process of transpiration reduces the Jlo and the A terms to perhaps 0.05Js. Therefore,

$S = Js(1 - 0.3) - (0.05 + 0.05 + 0.4)Js$
$= 700(1 - 0.8) = 140$ KWH per square meter

These considerations suggest that the effect of vegetation on the energy balance might be similar to the effect of whitening the inert surface. However, the presence of vegetation may offer the additional advantages of aesthetics, as well as reducing the quantity and intensity of storm-water runoff.

Water Relations of Green Roofs

To estimate the effect of "green roofs" (i.e., roofs covered with a shallow layer of a porous medium in which low plants are grown), assume an annual precipitation of about 1000 mm (40 inches). Now assume that the annual rate of evapotranspiration from a dense stand of xerophytes is likely to be about 50% of the potential evaporation, which we estimate to be about equal to the annual precipitation.

For a total roof area of 85 million square meters, the volume of runoff from bare roofs is about 85 million cubic meters. That amount can probably be reduced by half if the roofs are covered with vegetation.

The amount of water absorbed and stored in the growth medium (an artificial soil serving as the rooting medium for the plants to be grown) during each spell of rain (rain event, or rainstorm) depends on the porosity and depth (thickness) of the porous medium to be used. (By the term "spell of rains," we refer to a sequence of rainstorms that is not interrupted by a period of evapotranspiration).

If the depth of the medium is, say, 10 cm and the porosity 50%, then the so-called "water-holding capacity" is 5 cm. Each square meter can therefore hold 0.05 cubic meter of water (50 liters). Rain spells that do not exceed 5 cm (2 inches), if they follow a period of dryness (in which the "soil" moisture had been depleted), will produce no runoff at all. The greater the depth of the growth medium and the greater its porosity, the greater will be its effect in preventing runoff from the smaller storms and reducing runoff from the larger ones.

Hence we need to consider the local pattern of rainfall in order to assess the probable number of rain spells or storms that will produce no runoff from a given medium, and the possible reduction in the volume of runoff resulting from the rainstorms (or rain spells) that will exceed the available porous-medium storage and that will produce runoff of varying amounts.

Let us assume, hypothetically, that in a typical year there occur 50 spells of rain (one per week on average), each lasting two days, with a mean amount of 20 mm per rain spell. That amount can readily be absorbed into the envisaged porous substrate. Assume, furthermore, that the average potential evapotranspiration during the dry spell between rains is 4 mm per day. If the average dry spell between rains lasts about 5 days, and if the plants transpire at the full potential rate, then the moisture reserve in the growth medium will be depleted within five days. If, however, the rate of transpiration is below the potential evaporation rate (as is typical of the transpiration rate of xerophytes), then the moisture reserve may only be depleted in part. Clearly we also need to know much more about the specific water relations of the plants being considered for the green roof project to obtain a more accurate estimate.

In any case, it seems reasonable that a stand of plants growing in a porous medium capable of absorbing rainwater during spells of rain and of retaining that water for the subsequent use of plants, may well reduce the number of runoff-producing events (perhaps by half). Such a stand may also reduce the volume of runoff produced during spells of particularly heavy rainfall. Altogether, it seems reasonable that the presence of an absorptive layer of soil-like material, in which an actively transpiring stand of vegetation is growing, may well reduce storm-water runoff by some 50%.

For an area of 85,000,000 square meters, under a rainfall regime of 1,000 mm per season, the envisaged reduction amounts to some 42 million cubic meters.

General Comments and Caveats

The figures given above are very crude preliminary estimations, which need to be improved as more exact quantitative knowledge is obtained regarding the relevant variables and parameters. They can, however, serve (at least temporarily) as bench marks against which other estimates can be compared. Eventually, preliminary estimates will be supplanted by actual, measured data.

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